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THE NASA EXPERIENCE IN AERONAUTICAL R&D: THREE CASE STUDIES WITH ANALYSIS

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Recent policy studies have failed to provide adequate guidance for planning and evaluating the nation's program of aeronautical research and development (R&D). In particular, the government's use of experimental systems to bridge the gap between laboratory research and operational systems remains controversial. This thesis used retrospective examinations of NASA's work in aircraft noise reduction, powered-lift technology, and hypersonic flight technology to analyze the impact and effectiveness of such programs under four general circumstances that may justify government involvement in a market-driven economy. It concludes that the NASA proof-of-concept program has had mixed results, with technical goals more successfully accomplished than policy goals. The public benefits of the successes, however, far outweigh the costs of the disappointments. The thesis concludes that such demonstration programs in aeronautical R&D should continue, with a series of analytical and institutional changes to couple them more closely with policy goals.

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FOREWORD

This report was originally prepared as the author's doctoral dissertation, and was submitted to the Massachusetts Institute of Technology on May 4, 1987.

ACKNOWLEDGMENTS

The author would like to acknowledge the encouragement and support of Gerald M. Gregorek, Ted R.I. Greenwood, and Philip M. Smith, who have repeatedly urged and encouraged me to pursue such an enterprise over the past dozen years; of Professors Jack L. Kerrebrock and Eugene B. Skolnikoff, who guided and encouraged me through the long procedure of organizing and implementing an interdisciplinary program between two very different, yet logically connected, departments; of Professors George Rathjens and Robert Simpson, who guided the project both in formal classes and as committee members; and to Dr. Robert C. Seamans, who provided many valuable insights.

Dr. Robert E. Roberts of the Institute for Defense Analyses made this work possible by arranging the financial support and by mentoring the work through the Institute for Defense Analyses. His enthusiasm for research and concern for younger staffers is rare outside a university environment, and is greatly appreciated. Likewise, I appreciate the comments of the IDA review panel. Not all of their views are reflected in this report, but all were examined and appreciated.

Many people at the National Aeronautics and Space Administration (NASA) and in various companies contributed to the conduct of this research. Rather than attempting to list them all in this introduction, I have attempted to acknowledge them with specific references.

ABSTRACT

Recent policy studies have failed to provide adequate guidance for planning and evaluating the nation's program of aeronautical research and development (R&D). In particular, the government's use of experimental systems to bridge the gap between laboratory research and operational systems remains controversial. This thesis uses retrospective examinations of NASA's work in aircraft noise reduction, powered-lift technology, and hypersonic flight technology to analyze the impact and effectiveness of such programs under four general circumstances that may justify government involvement in a market-driven economy. It concludes that the NASA proof-of-concept program has had mixed results, with technical goals more successfully accomplished than policy goals. The public benefits of the successes, however, far outweigh the costs of the disappointments. The thesis concludes that such demonstration programs in aeronautical R&D should continue, with a series of analytical and institutional changes to couple them more closely with policy goals.

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GLOSSARY

As an interdisciplinary work, this study combines concepts from aeronautical engineering, political science, and economics. Among the terms, acronyms, or concepts that recur throughout this work are:

Appropriability: The ability of a firm or organization to capture the benefits of an investment.

Externality: Occurs whenever a transaction delivers costs or benefits to firms or individuals not party to it.

Net Present Value (NPV): For a given cash flow and interest rate, an "equivalent amount" can be determined at any point in time. NPV is value:

$$NPV(i)_j = \sum_{t=0}^{n} F_{jt} \; (1 + i)^{-t}$$

where i = interest rate

F_{jt} = net cash flow for investment proposal j at time t.

Internal Rate of Return (IRR): Interest Rate that reduces NPV of a cash flow sequence to zero. Value of i_j^* that satisfies:

$$0 = NPV(i_j^*)_j = \sum_{t=0}^{n} F_{jt}(1 + i_j^*)^{-t}$$

Private good: Any activity to which an economic value can be attached by a private firm or individual, conceptually determined as:

$$NPV_j = \sum_{t=0}^{n} V_{j,t} \; (1 + i)^{-t}$$

where j = firm or individual

t = time

n = number of time units considered

V = valuation placed on activity by unit j at time t

i = interest rate.

Public good: Economic value of an activity when integrated across all of society, conceptually defined as:

$$NPV = \sum_{j=1}^{m}\sum_{t=0}^{n} V_{j,t} \ (1 + i)^{-t}$$

where j = firm or individual

m = number of firms or individuals comprising society

t = time

n = number of time units considered

i = interest rate used by unit j.

Pareto improvement: Criteria whereby a project in question, to be considered economically feasible, must be capable of producing an excess of benefits such that everyone in society could, by a costless redistribution of gains, be made better off.

Experimental aircraft: An aircraft intended to investigate one or more phenomenon through flight research, where the investigations concern some technology or configuration of the aircraft itself (Examples: X-15, XV-15) without intent to place the aircraft into serial production for operational use. Subcategories include:

Proof-of-concept: an experimental program designed to test a system and establish feasibility--generally places more emphasis on technical characteristics, a precursor to technology validation.

Demonstration: an experimental program synonymous with experimental aircraft, encompassing both proof-of-concept and technology validation features.

Technology validation: an experimental program intended to provide not only data but also field experience, in order to provide data in such areas as maintainability, reliability, and operating cost.

Research aircraft: An aircraft that serves as a platform for carrying instruments or experiments, not necessarily dealing with the airframe itself (Example: ER-2).

Prototype: An aircraft or engine intended to precede serial production and designed to specifications prepared to procure an item that will meet an operational requirement.

ACEE	Aircraft Energy Efficiency program
IPAD	Integrated Program for Aircraft Design
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
OAST	Office of Aeronautics and Space Technology
AA	Associate Administrator
OSTP	Office of Science and Technology Policy
QCSEE	Quiet Clean STOL Experimental Engine program
QCGAT	Quiet Clean General Aviation Turbine program
RTOP	Research and Technology Objectives and Plans
REFAN	NASA Program to replace fan stage of JT-8D engine

EXECUTIVE SUMMARY

What role should NASA, as compared to end users of technology such as the military or private industry, have in aeronautical research in the 1990s? Even if some research role is justified, how is the line for government involvement to be drawn in the spectrum between basic research and product development? Despite continuing debate and numerous government reviews, and despite the importance of the answers to these questions not only to NASA, but also as a model to other areas of government involvement in R&D, there remains no broad consensus on an appropriate Federal policy for aeronautical R&D. A quarter-century of NASA experience now exists in aeronautics. The purpose of this study was to examine the historical record and derive from it general guidance for making future policy decisions.

Three case studies form the core of the analysis, covering NASA's programs in aircraft noise reduction, short takeoff and landing aircraft, and hypersonic flight. In each of these cases NASA involvement spanned the full spectrum from basic research through demonstration hardware. Together, they cover not only the full range of vehicle performance but also the range of clients and customers served by NASA. Although by no means exhaustive, they are representative of the overall NASA program and thus provide a sound basis for a preliminary analysis. Eight general conclusions emerge from the study:

1. **NASA's basic role in aeronautics should be to carry out research to build the technological infrastructure and provide opportunities for dramatic technological advances in areas where the tax-paying public will benefit but which no one airline, aircraft, or engine company has the incentive to pursue.** Historically, NASA's specific roles have been to: (a) act as an information clearinghouse and national corporate memory; (b) provide direct support to other government agencies; (c) generate new technological opportunities through a program of focused research; (d) develop specific technological options to assist in solving identified national problems. These roles remain generally valid, but as the industry has matured it has become increasingly important for NASA to sharpen its analysis of why government investment is appropriate. Technical opportunity is a necessary, but no longer sufficient, criterion.

2. NASA's most important role in aeronautics has been and should remain to provide technology to other users. NASA has proved particularly adept at taking existing but unexplored concepts and developing them to the point that they can be applied in practical systems. This process is most appropriately described as *focused research*.[1] The key ingredients in focused research include: (a) the availability of experienced people from many disciplines, (b) dedicated research facilities (i.e., not also in use for production development), and (c) a research-oriented environment. The results form the basis upon which specific developments can be based. Because of a paradox--that the research itself takes a long time to conduct, and yet may be called upon on relatively short notice to meet some perceived national need--the program of focused research must be funded consistently.

3. NASA's demonstration programs have had mixed results. In general, the technical goals laid out for these programs have been accomplished more successfully than the policy goals. The public benefits of the successes, however, appear to far outweigh the costs of the disappointments. Occasionally, demonstration programs have been judged necessary to take technology out of the laboratory, in order to provide a focus for laboratory research, to provide unique data that cannot be otherwise obtained, or to build confidence among potential users. In many of the examples encountered in the case studies, the work was technically successful but never applied--usually for economic reasons. In a few cases the work led to a technological dead end. But enough cases have been successfully transitioned on to development programs, where they have produced quantifiable public benefits, to make a preliminary judgment that such programs have been a justifiable public investment. The JT-8D-109 REFAN engine, for example, was never adopted for the retrofit purposes for which it was originally intended, but served as a crucial element in the creation of the MD-80 family of derivative aircraft. To date some 1800 JT-8D-200 series engines have been sold, with a fuel savings from these engines compared to earlier models of approximately $2.7 billion. Likewise, although the Advanced Turboprop program has

1 Examples can be drawn from every case study: for example, sound-absorbing material (SAM) for aircraft noise reduction. The concept of SAM did not originate in NASA, and had in fact been used before NASA ever entered the field. But its potential utility was estimated to be very low and it was not being actively pursued. Beginning in the mid-1960s NASA stepped in and was able to combine theoretical analysis with a unique flow-testing facility to produce a rapid increase in SAM effectiveness. This was then tested in actual engine designs under NASA auspices. SAM alone allowed some existing aircraft to meet Federal noise regulations, and the materials have since been used in the nacelles of essentially every modern commercial jet engine.

not reached production status at this writing, the several systems in product development can still be expected to produce a public savings (in current prices) of about $2.4 billion. Similarly, the XV-15 Tilt Rotor, which cost NASA around $25 million, has led directly to the V-22 Osprey currently under development for all four military services (and with commercial derivatives likely to follow). Over 900 V-22s are currently planned for procurement, which compared with available options should produce over $2 billion in public savings.[2] These three examples alone provide gross public benefits of over $7 billion at a NASA cost of perhaps $250 million. The total NASA investment in all aeronautics during the past 25 years has been only about $8.3 billion. It would appear that if the above major successes are representative that the total public benefit would outweigh the costs of those initiatives that did not meet their original expectations.

4. NASA's demonstration programs should continue, but the criteria for determining whether a demonstration program is justified should vary depending on the goal that is being pursued. Many of the NASA programs appear to have been driven largely by technological opportunity; when the agency has examined the economics of new technology, it has usually stopped short of asking why government involvement is specifically required or how responsibility should be divided between public and private sectors. The study suggests that there are three basic strategies that NASA should pursue, depending on whether private sector incentives are positive, negative, or neutral:

Private sector incentives perceived positive. In general, the government should stay out of areas where the private sector has positive economic incentives. The study notes the severe distortions to a free market that exist in aeronautics, and concludes that even when positive, appropriable economic benefits may appear to exist for the private sector, various factors may lead the private sector to undervalue the research. The most common case is where the benefits are not fully appropriable (i.e., a development offers both public and private benefits) and the costs are not readily allocable. In such cases, the government's goal should be to secure public benefits at minimum cost by using government R&D to stimulate the private sector. Since public and private benefits are thus linked, the government should continue its R&D either until the net present value seen by the private sector becomes positive (indicated by the launch of a major private initiative), or until the

2 As this Report went to press, the program was under Defense Department and Congressional budget review.

net present value seen by the public sector becomes negative. The key point is that government R&D managers need to be aware, and take into consideration, cost-benefit calculations of both the public and private points of view. In most of the case studies examined, they did neither.

Private sector incentives are perceived negative. Just as market economics sometimes understate net public benefits of an activity in private-sector calculations, so they sometimes understate public disbenefits (in the absence of regulations, for example, airlines see no net cost in the production of noise, while people living under a flight path obviously do). In such cases government regulation is frequently a response. Such regulatory intervention has occurred extensively in aeronautics, and it inevitably shifts incentives for R&D. In such situations, NASA should have two goals. The first is to provide options and data to support the rational and effective promulgation of rules, acting as the interface between a reluctant industry and an administrative (i.e., essentially non-technical) regulatory agency. The second goal is to provide a "technology push" to complement the "market pull" of regulation, with the technology available in advance of (or at least parallel with) the regulation. Such parallelism allows a much more realistic assessment of the true regulatory impact. The noise case study strongly suggests that Federal regulatory agencies act, in practice, as adjudicatory bodies, choosing between a selection of currently available options. Industry inevitably promotes the option imposing minimum impact on their operations. Thus, NASA filled a unique role by developing and by demonstrating new options. Although many in NASA viewed their noise reduction demonstration programs as going far beyond the agency's proper role, in retrospect some of these programs do not appear to have gone quite far enough.

All the goods are public, so that private sector incentives are essentially neutral. The issue here is not so much whether the government should be involved in R&D, but whether the responsibility for R&D should be delegated to a dedicated R&D agency like NASA or reside in the cognizant "operational" agency such as DoD or the FAA. The analysis presented in this study concludes that the long-term, focused research is better suited to a dedicated R&D agency where it is not forced to compete with existing systems.

5. An agency with a broad institutional charter is required to comprehensively assess the true public value of developing technologies. If each of the situations identified above could be compartmentalized, it might be still more efficient to have operational agencies pursue R&D. It is characteristic of aeronautical research, however, that the ultimate application is often unknown even well into the demonstration phase. Many aeronautical R&D programs have potential benefits in several areas. For example, STOL aircraft could be used to deliver passengers to small airports close to urban areas, or to deliver troops to unprepared airports near the front lines; the tilt-rotor could be used to commute between city centers or between aircraft carriers; or quiet engines could be used to reduce annoyance of residents near civil airports or to provide stealth qualities for military aircraft. This tendency of most new technologies to have potential applications in several fields means that any single potential user will under-value the technology as a whole. Further, some operational agencies are legally prohibited from considering factors outside their charter.[3] A dedicated R&D agency is able to span the categories and integrate the known elements of the total cost and benefit of a technology. In aeronautics, NASA is uniquely suited to this role.

6. NASA should avoid a generalized role in prototyping or initiating production programs. Despite confirming the need for demonstration programs, the study found no obvious justification for a generalized NASA role in prototyping or commercial development. The reason for this is simply that however much NASA attempts to consider market or operational considerations in its analysis, there is no institutional mechanism for making them fiscally accountable for such decisions. In light of this lack of closure, it is economically inefficient to have NASA making production decisions.

The study found essentially no attempts by NASA to move into such a role; indeed, the agency has always avoided it. What the study did find, however, was frequent confusion between "experimental" aircraft on the one hand and "prototypes" or "commercial developments" on the other. The working definition suggested for "prototype" is that if the system works as intended, it will meet a specific operational requirement and could lead directly to a production vehicle. Thus, prototypes should be highly driven by production and operational considerations, which NASA should usually leave to others. "Proof of concept," "technology validation," or "experimental" systems, in contrast, seek to test concepts but have no pretense of leading to a production system. As such, the degree of technological risk that can be accepted is higher, while costs can be reduced through the use of modified, rather than new, equipment. These are quite appropriate for NASA involvement.

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3 The Department of Defense, for example, is restricted by the Mansfield Amendment to R&D with "foreseeable military applications."

7. NASA's lack of operational responsibilities in aeronautics is an important key to its effectiveness in conducting R&D. It is commonly assumed that only an operational agency can truly understand the problems it faces and thus that agencies like the DoD or FAA should have primary responsibility for R&D in their areas, with NASA playing a supporting (if any) role. All of the case studies suggest that while "operational" agencies appear to do an adequate job supporting evolutionary, incremental improvements to existing technologies, they do less well in nurturing radical innovations. NASA's lack of operational responsibilities in aeronautics is found to be beneficial to its role as a research agency. The Air Force's treatment of STOL or scramjets, or the FAA's involvement with supersonic transports or quiet engines, suggest that operational agencies alternate between seeing no application for a given technology--and thus no justification for supporting R&D--and pressing for an immediate application, with a prototype of an operational system needed as rapidly as possible. Further, there is a tendency for research programs to be perceived as competition to development of current-generation systems. This is precisely the wrong environment for the type of focused, long-term research so important to the development of a strong technological base. A similar situation may be noted within NASA regarding the space program, where NASA is itself an operational agency.

8. NASA should be a major technical participant in all experimental aircraft. In general, cooperative programs between NASA and other institutions seem to have fared well. Interagency coordination seems to have been most successful either when the interagency effort was being steered from above (as when the Office of Science and Technology led the governmental noise reduction effort) or when NASA's partner agency did not have a primary mission in aviation *per se*, but rather saw it as a means to an end. The joint rotorcraft program conducted with the Army or the propeller noise reduction work with the EPA are examples of this success.

The overall conclusion from the case studies examined here is that, despite the long payback period and uncertain returns, aeronautical R&D is inherently practical. Every day the nation's commercial and military well-being is shaped by aeronautical vehicles, which are directly and continuously influenced by aeronautical research and development. In this sense the field is fundamentally different from others such as high-energy physics or space science. The logic and arguments used to plan and defend the NASA aeronautics program should be grounded in an explainable and constantly updated evaluation of the potential national worth of the program and its elements.

INTRODUCTION

This work grew out of a shared frustration that the analytical foundations upon which public policy for aeronautical R&D is based have not kept pace with either the technology or the general environment in which aeronautics operates. In the author's case this came from participation in an abortive attempt to develop an aeronautics policy within the Office of Science and Technology Policy (OSTP) during the late 1970s. In the case of one thesis supervisor (Kerrebrock) the frustration was a product of his experience as the NASA Associate Administrator participating in a similar study under the Reagan Administration. Together, we agreed that the topic warranted a detailed examination in a scholarly, rather than political environment.

An interdepartmental doctoral dissertation at MIT seemed to be an ideal vehicle for such a study. By constructing a unique program in the field of "Aeronautics and Public Policy" it was possible to draw together the range of coursework and supervising faculty needed to perform such a study.[3] Although it has been aided by numerous officials and employees of NASA, it is perhaps unique in that no direct financial support for the study has been provided by NASA. Instead, support has been provided by the private but non-profit Institute for Defense Analyses (IDA) as a part of its ongoing independent research program aimed at addressing timely issues that impact national security.

Historically, most aeronautical research has been driven by the performance requirements of military aircraft.[4] The technology has been developed at government expense and then proven on military aircraft. After extensive operational experience with

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3 The thesis committee was drawn half from the Department of Aeronautics and Astronautics and half from the Department of Political Science. Members included: Dr. Jack L. Kerrebrock (R.C. MacLaurin Professor, Associate Dean for Engineering, and former head of Department of Aeronautics and Astronautics); Dr. Eugene B. Skolnikoff (Professor of Political Science and Director, Center for International Studies); Dr. Ted R.I. Greenwood (Associate Professor of Political Science, Columbia University); Dr. Robert W. Simpson (Professor of Aeronautics & Astronautics and Director, Flight Transportation Laboratory); Dr. George W. Rathjens (Professor of Political Science); and Dr. Robert C. Seamans, Jr. (Senior Lecturer in the Department of Aeronautics and Astronautics).

4 The 1972 DoD/NASA/DoT Study *Research and Development Contributions to Aviation Progress* (RADCAP) identified 51 significant technological advances made in U.S. aviation between 1925 and 1970; government research was responsible for 45 of these, with direct military sponsorship responsible for 35.

the military, the technology has been available for use in civil applications with relatively low technical risk or uncertainty. This transfer has been facilitated both by the industrial structure (where the same companies produce both military and civil aircraft) and by a conscious government policy of encouraging such transfer, especially through the use of a civil agency (first NACA, the National Advisory Committee for Aeronautics, then NASA) as the government agency responsible for technology development. This combination of government market "pull" combined with technology "push" is widely credited with allowing the United States to attain world leadership in both military and civil aviation.[5]

As commercial aviation matured during the 1960s, however, less direct transfer became possible from military development programs. Concern that several promising civilian technologies were not being adequately pursued led to an increased NASA role in civil aircraft. The key to this expansion was a philosophy known as "proof of concept," which argued that it was not enough for NASA merely to develop technology and components in the laboratory, but that it should develop, demonstrate, and prove them in experimental systems which could be tested in near-operational conditions.

This philosophy has led to a number of aeronautical demonstration programs during the 1970s, many of which are discussed in succeeding chapters. The NASA approach was paralleled in other fields, particularly energy and the environment. But by the late 1970s government-sponsored demonstration programs were generally in decline, and by the early 1980s questions were being raised as to whether they were really an appropriate government activity at all. At the same time, however, other suggestions were being made to the effect that the government should expand its role in industrial policy, and that demonstration programs might play a key role. Largely lacking in this discussion, however, has been any attempt to examine specific historical programs retrospectively and determine how successful they have been in meeting the various goals and expectations held for them when they were initiated. This study begins that process.

The work accepts without question the propositions that aeronautics is important to the nation's defense and economy, and that much remains to be learned and done in the

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5 See David C. Mowery and Nathan Rosenberg, "The Commercial Aircraft Industry," in Richard R. Nelson, Ed., *Government and Technical Progress, A Cross-Industry Analysis* (Pergamon Press, 1982).

areas of research and development.[6] Likewise, it does not attempt to address ideological questions about whether the government should or should not intervene in the private sector regardless of its effectiveness. Instead, it adopts a pragmatic approach, examining both the technical and the political impact of selected historical examples, and drawing from these examples conclusions about the effectiveness of such programs in meeting various goals.

The general approach taken by this research is threefold. First, it seeks to identify general circumstances that justify government involvement. Then for each category it identifies and studies historical examples. From these, it attempts to specify more or less objective criteria for planning and evaluating future programs. Throughout the study, a specific emphasis is placed on demonstration programs and their role in the R&D process. There are many terms used to describe such programs, many of which seem synonomous but in fact have different shades of meaning. This study will use the following specific definitions:

Experimental aircraft: An aircraft intended to investigate one or more phenomena through flight research, where the investigations concern some technology or configuration of the aircraft itself (Examples: X-15, XV-15) without intent to place the aircraft into serial production for operational use. Subcategories include:

Proof-of-concept: an experimental program designed to test a system and establish feasibility. Generally places more emphasis on technical characteristics, a precursor to technology validation.

Demonstration: an experimental program synonymous with experimental aircraft, encompassing both proof-of-concept and technology validation features.

Technology validation: an experimental program intended to provide not only data but also field experience, in order to provide data in such areas as maintainability, reliability, and operating cost.

Research aircraft: An aircraft that serves as a platform for carrying instruments or experiments, not necessarily dealing with the airframe itself (Example: ER-2).

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6 These issues have been fully treated in reports such as the Office of Science and Technology Policy's *Aeronautical Research and Technology Policy* (Executive Office of the President, November 1982), and the National Research Council's *Aeronautics Technology Possibilities for 2000: Report on a Workshop* (National Academy Press, 1984). I assume that anyone reading this report has a basic familiarity with these issues.

Prototype: An aircraft or engine intended to precede serial production and designed to specifications prepared to procure an item that will meet an operational requirement.

The chapters that follow are divided into three general sections. The first (Chapters 1-3) is primarily descriptive in nature, defining the terminology, expanding on the three analysis frameworks introduced here, and providing historical context. The first chapter introduces three major approaches to analyzing government roles in aeronautical R&D, and concludes that the two most commonly-used approaches pose policy questions that are left unresolved. The second chapter provides an overview of the first quarter-century of NASA aeronautics, beginning with the program inherited from the National Advisory Committee for Aeronautics (NACA, NASA's institutional predecessor) and tracing the program through a period of decline (where resources were shifted to space exploration) to revitalization (based largely on the proof-of-concept approach) to the present period of uncertainty. The third chapter extends this review by examining in more detail three specific case studies.

The second portion of the study (Chapters 4-8) concentrates on the development of the motivation-oriented framework, reviewing the general case for government support of aeronautical R&D in a market economy (Chapter 4) and then extending the analysis based on four major circumstances that may justify more extensive government intervention (economic, regulatory, military, and international). These chapters concentrate on the development of simple models that allow application of investment criteria such as cost-benefit analysis whenever possible.

The final chapter draws together conclusions from the various cases and circumstances. Overlap between categories is found to be one of the primary reasons that an independent agency like NASA is required to conduct the government's research, rather than dividing the research between cognizant operational agencies. Although the study confirms many familiar conclusions, the chapter focuses on those instances where the NASA experience seems to counter conventional wisdom or general policy.

Although this study only begins the process of distilling lessons from the NASA experience, the results may hold interest for several pursuits. The most important is probably in the planning and conduct of NASA's own aeronautical R&D, both within the agency itself and in other institutions that must oversee or interact with NASA. The results are also highly relevant to the defense community, which is one of the most important users of NASA technology and which is itself currently struggling with the issue of what role demonstrations and prototypes should play in the development process. Finally, the study may make some small contribution to more general discussions of R&D or industrial policy. The nation's industries have only begun the adaptation to a new regime of global economic competition based on technology, and the proper division between public and private responsibilities is one of the most important items for discussion on the national agenda.

CHAPTER 1. ROLES AND MISSIONS OF NASA IN AERONAUTICS

The Federal government supports research and development not as an end in itself, but rather as a means of advancing other societal interests. In aeronautics, the Federal government's two primary responsibilities are national defense, where its role is constitutionally mandated, and the civil air transportation system, where it has preempted state and local authorities in order to ensure and promote the development of a safe, effective, and uniform air transportation system. These responsibilities have led to a wide range of Federal involvement in aeronautics, including large-scale military procurement, economic regulation of and subsidies to the airlines, airworthiness standards for aircraft and aircrews, and management of the nation's civil air traffic control system. In addition, the aeronautics industry is affected by all the government policies that influence business in general, such as tax and monetary policy, antitrust restrictions, patent policy, tariffs, financing assistance for international sales, and environmental, health, and safety regulations. These involvements have led both directly and indirectly to government financing of aeronautical research.

There are many different ways of analyzing the government's efforts in aeronautical R&D. This chapter will introduce three. The first, which I will call the "stage of research" approach, divides R&D into its component phases and classifies each project or activity according to its position along a spectrum. The second approach, referred to here as the "mission-oriented" approach, attempts to relate each specific program element to an organization's overall charter and institutional goals. The third approach is to begin with the question of what the government hopes to gain from a particular program, and compares the potential costs and gains with other choices. I will refer to this as the "motivation-oriented" approach.

Each approach has its own utility and limitations. The stage-of-research approach, for example, is almost a necessity for actually managing R&D projects on a day-to-day basis, while the mission-oriented approach is well suited to oversight reviews such as might be conducted by Congress. Each of these, however, has a specific limitation in terms of formulating public policy. The stage-of-research model asks "how far down the spectrum should the government properly go?" but the supporting theory cannot by itself provide a complete answer. Similarly, the mission-oriented approach points up the tension between the need for long-term, high-risk research, and near-term solutions to specific national problems, but provides no guidance as to how these demands should be met or balanced. To resolve these questions it is necessary to develop the third analysis framework, based on the proposition that the appropriate level of government R&D depends on the problem that the government is trying to solve. This chapter begins that development, which will be completed on a circumstance-by-circumstance basis in later chapters.

1.1 THE STAGE-OF-RESEARCH MODEL

The most common model used in discussing aeronautical R&D uses stage-of-research as its first-order classifier. Figure 1-1 illustrates how the aeronautical enterprise can be defined as a spectrum, extending from education and basic research all the way through production, testing, and use in service. The spectrum has several basic characteristics as it moves from education to production: (1) costs tends to increase, with a unit of basic research much less costly than product development; (2) technical uncertainty decreases; (3) the ability of a firm to capture the benefits of its investment (appropriability) increases, and (4) the time scale for an idea to progress across the spectrum can be very long.

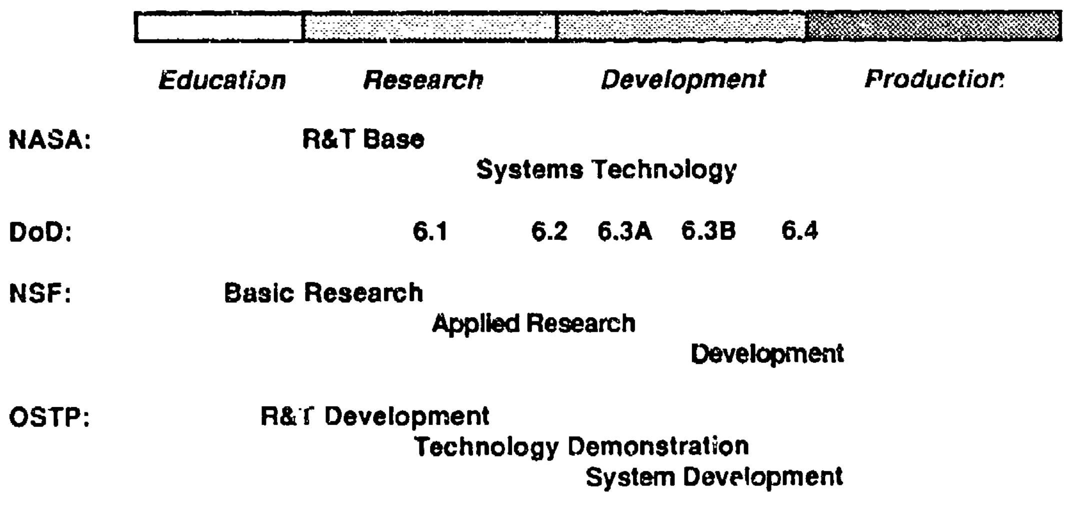

Figure 1-1. The research and development process is typically portrayed as a spectrum, with education and basic research at one end and the solving of operational problems at the other. How the spectrum is divided is largely an issue of semantics; this figure illustrates some of the more common divisions.

NASA bases its aeronautics budget on this model, broadly classifying work as either "Research and Technology Base" or "Systems Technology."[7] This view of the research and development process as a spectrum is shared by most other government agencies involved with R&D, although there are semantic differences in the divisions. The National Science Foundation, for example, classifies work as either "basic research", "applied research," or "exploratory development." The Department of Defense divides its Defense Research & Engineering (DRE) work into the categories of "Research" (Category 6.1), "Exploratory Development" (6.2), "Advanced Development" (6.3), or "Engineering Development" (6.4).

There are historical, programmatic, and theoretical reasons for NASA's use of stage-of-research as the first-order classifier. Historically, one of the government's original roles was to bridge the gap between universities (which conduct primarily basic research) and industry (which focuses primarily on development). Even within the NASA program, it has been logical to differentiate between programs based on stage of research; the technical and managerial approaches differ drastically between a basic research effort and a development program, as do costs, schedules, importance of technical versus economic uncertainties, and expectations. Finally, most economic theories about government investment in R&D are also structured around the stage-of-research differentiation. The uncertain returns, long payback time, and low appropriability have led many observers to conclude that private industry tends to focus on near-term product development, often at the expense of basic research. As will be discussed in Chapter 4, these arguments suggest the general philosophy that government involvement in R&D is most appropriate at the basic research level and generally less appropriate at more advanced stages of development.[8]

With stage-of-research almost universally used as the first-level classifier, it is natural that policy questions also be posed in terms of this structure. This has indeed

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7 As will be discussed in Chapter 2, the number and exact name of the categories have changed several times, but the use of stage-of-research as a first-order classifier has been consistent. NASA uses discipline and application as second- and third-order classifiers. The disciplines typically follow those found in a university environment, such as propulsion, structures and materials, aerodynamics, human factors, or controls. The applications tend to divide programs by flight regime, for example: rotorcraft, general aviation, subsonic cruise aircraft, supersonic aircraft, etc.

8 This argument is further supported by the generally poor experience of the Federal government in advanced development of civil technology. In particular, see George Eads and Richard R. Nelson, "Governmental Support of Advanced Civilian Technology: Power Reactors and the Supersonic Transport," *Public Policy*, 19 (1971), pp. 403-427.

happened, with repeated attempts to define the government's "appropriate" role in aeronautical R&D in terms of stage-of-research. In 1966, for example, a Senate report observed "an underlying congressional conviction that NASA...should step from its traditional role of 'research only' into the development area."[9] In 1982 the Office of Management and Budget announced "technology development and demonstration projects ...should be curtailed as an inappropriate Federal subsidy,"[10] and in 1983 the NASA Associate Administrator in charge of aeronautics research stated "I think the basic issue now is where in the spectrum from basic research to full-scale development the line should be drawn for government funding."[11]

This approach, and the problems it can bring, is best illustrated by a week-long workshop held in 1980 by the National Research Council.[12] The workshop brought together almost 80 individuals from all sectors of aeronautics and related fields. The workshop's organizers defined eight possible "roles" for NASA, including: (1) providing national facilities and expertise, (2) conducting fundamental research, (3) developing generic technology, (4) developing technology for specific vehicle classes, (5) demonstrating technology through lab-condition tests, (6) validating technology through field-service tests, (7) developing prototypes, and (8) establishing operational feasibility by developing and operating demonstration systems. Four different panels (one each for military aviation, transport aircraft, general aviation, and rotorcraft) then attempted to develop "role/discipline matrices" rating NASA's appropriate involvement as major, moderate, minor, or nonexistent for each role in each of six disciplines (aerodynamics, structures and materials, propulsion, electronics & avionics, vehicle operations, and human engineering). A typical result is shown in Figure 1-2.

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9 Library of Congress, *Policy Planning for Aeronautical Research and Development*, 89th Congress, 2nd Session, Document #90, May 19, 1966, p. 16.

10 Office of Management and Budget, Fiscal Year 1983 Budget, *Special Analysis K, Research and Development*, Government Printing Office.

11 Statement of Jack L. Kerrebrock, *NASA Authorization for Fiscal Year 1983*, 97th Congress, 2nd Session, Serial Number 97-112.

12 The NRC workshop is used here because it was judged by the author to be relatively free of political overtones compared to other studies. See Aeronautics and Space Engineering Board, Assembly of Engineering, National Research Council, *NASA's Role in Aeronautics: A Workshop*. (Washington, DC: National Academy Press, 1981). Volumes I-VII.

Roles	Disciplines					
	Aero-dynamics	Structures and Materials	Propulsion	Electronics and Avionics	Vehicle Operations	Human Engineering
National Facilities and Expertise	1	1	1	1	2	1
Research	1	1	1	1	2	1
Generic Technology Evolution	1	1	1	1	2	1
Vehicle Class Technology Evolution	1	1	1	1	2	1
Technology Demonstration	$1^{a,b}$	$1^{a,b}$	$1^{a,b}$	$1^{a,b}$	$2^{a,b}$	$1^{a,b}$
Technology Validation	1^{a}	1^{a}	1^{a}	1^{a}	2^{a}	1^{a}
Prototype Development	$3^{a,c}$	$3^{a,c}$	$3^{a,c}$	$3^{a,c}$	$3^{a,c}$	$3^{a,c}$
Operations Feasibility	$2^{a,d}$	$2^{a,d}$	$2^{a,d}$	$2^{a,d}$	$2^{a,d}$	$2^{a,d}$

NASA ROLE CODE:	NOTES:
1. Major Role	(a) When national interest dictates.
2. Moderate Role	(b) Where components must be combined to evaluate the whole or where experimental flight testing is required.
3. Minor Role	(c) With Congressional approval.
*- No Role	(d) High risk—only way to evaluate.

* If a proposed project or program initially falls in a recommended moderate, minor, or no-role category, but, following review of its merits on an individual case basis, is deemed to be a desirable undertaking by virtue of its being in the national interest, or mandated by the Congress or as a result of review it is concluded there are other overriding circumstances, then NASA's role for that project or program would be elevated to a major one (i.e., Category 1).

Figure 1-2. A typical result from the 1980 NRC workshop, showing the "role/discipline matrix" developed for Air Transport.
Source: *NASA's Role in Aeronautics: A Workshop*, Vol. I, p. 12.

In general, the assembled experts from industry and the services confirmed the status quo, agreeing that NASA should not be in the business of designing or building prototypes but should be conducting basic research.[13] Beyond that, the panel recommended NASA should be involved in "Technology Demonstration" and "Technology Validation" "when, after an assessment of each individual case, the potential benefit to the country is considered great."[14] As to how such benefits were to be measured, distributed, or weighed against costs, the workshop was silent. In effect, the workshop focused on

13 One role that NASA has never adopted, but certainly had open to it at times, was that of undertaking the development of actual aircraft designs. In the area of military aircraft, the issue never seriously arose, because of the long tradition of the military services in that area. Such a role has, however, been suggested for the government on several occasions. An example was the Prototype Aircraft Act, passed by Congress in 1950 to promote the development of turbine-powered transport aircraft (see *Policy Planning for Aeronautical R&D*, S-90, p. 34). Although the bill provided $12.5 million, industry was unenthusiastic and no funds were ever spent. The government tried to stimulate commercial development again in 1964, offering a $100,000 design contract for a small transport to replace the DC-3 (see S-90, p. 237). Only three entries were received (and one of those was disqualified) and the FAA withdrew the competition on the grounds that no truly new designs had been produced. The government sponsored the commercial certification of the C-141 transport in 1963 in hopes of producing an economical commercial cargo plane, but no commercial sales were ever made. Of course, the biggest example was the SST program, where the Federal government invested over $700 million for the design and construction of a prototype, before Congress canceled the program on economic and environmental grounds in 1971.

14 *NASA's Role in Aeronautics*, Vol. I, p. vi.

applying criteria without ever really defining them. For example, no guidance was given as to why it is appropriate for NASA to support General Aviation "technology validation" in structures and materials but not in aerodynamics, or why it is appropriate for NASA to establish "operations feasibility" in rotorcraft but not commercial transports. The results are highly temporal and subjective, and thus unlikely to make a lasting contribution towards defining policy. The extremely subjective nature of the NRC recommendations is not unique. After several decades of addressing the problem in this manner, satisfactory decision criteria have yet to emerge. This suggests that the problem is more fundamental than the makeup of any particular group, but rather, it is a structural problem with this particular analysis framework.

1.2 THE MISSION-ORIENTED APPROACH

An alternative to the stage-of-research model is to analyze programs in terms of their contributions towards meeting agency goals. The most specific enunciation of NASA's missions remains its original charter, the National Aeronautics and Space Act of 1958 (P.L. 85-568, as amended). Of the eight objectives Congress specified in this act, three contained direct references to aeronautics:

> The improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical vehicles;
>
> The establishment of long-range studies of the potential benefits to be gained from aeronautical activities;
>
> The preservation of the U.S. leadership in aeronautical technology;...

Four additional objectives implicitly specified for aeronautics:

- -- The expansion of human knowledge of phenomena in the atmosphere;
- -- Transfer of knowledge and technology to other government agencies;
- -- International cooperation in scientific research;
- -- Effective utilization of scientific and engineering resources, with close cooperation among government agencies to avoid unnecessary duplication of effort, facilities, and equipment.

To accomplish these objectives, NASA was empowered to plan, direct, and conduct "aeronautical activities;" to arrange for participation by the "scientific community" in NASA research; and to provide for "the widest practicable and appropriate dissemination of information." "Aeronautical activities" were defined to include both "research into the problems of flight within the atmosphere" and "the development, construction, testing, and operation of aeronautical vehicles for research purposes."

Broad goals such as "preserving national leadership in aeronautics" are insufficient for analysis purposes. Drawing from the NASA charter and from the historical development, NASA appears to have four basic missions in aeronautics:

- Acting as an information clearinghouse and national corporate memory;
- Providing direct support to other government agencies and their contractors;
- Generating new technological opportunities through a strong technology base;
- Developing specific technical options to solve identified national problems.

NASA structures neither its budget nor its organization around these missions, so the elements of the program devoted to meeting each mission are intertwined. Perhaps the most important contribution toward fulfilling its role as a national information clearinghouse and corporate memory is NASA's maintenance of a large in-house research capability at its research centers. Unlike the services, which rotate military personnel frequently and maintain small in-house civilian staffs, NASA research centers have tended to retain their staffs for long periods of time. In addition, NASA holds periodic conferences and workshops that focus on a selected area of technology, publishes extensive series of reports covering both internal and contracted research results, and produces special publication series that deal with historical topics or unique applications. To catalog aerospace material, NASA publishes the Scientific and Technical Abstract Report (STAR) series, operates a computer data base system (RECON), and sponsors the International Aerospace Abstract series. While no empirical studies are available on the benefits of this corporate memory effect, both interviews and experience suggest that it appears to have resulted in large savings of effort that would otherwise be duplicated repeatedly.

One of the original arguments for establishing dedicated government aeronautical R&D labs was that many of the facilities were too expensive for the services or private industry to afford individually, and that publicly-owned facilities could be shared in the interests of all. Over the years this inventory of facilities has built up so that by 1982 NASA counted 42 major aeronautical research facilities among its centers, valued at about

$4 billion.[15] Almost 40 percent of the usage of these facilities comes from outside of NASA.[16] Especially important are the 17 "unique national facilities" listed in Table 1-1.

Table 1-1. Summary of NASA's Unique National Facilities in Aeronautics.
Source: Office of Science and Technology Policy,
Aeronautical Research and Technology Policy

Facility	Center	% of use by		
		Civil	Military	NASA
12' Pressure Tunnel	Ames	18	32	50
Flight Sim. for Advanced Aircraft	Ames	10	55	35
Vertical Motion Simulator	Ames	25	15	60
RPV Simulation Facility	Dryden	0	0	100
Aeronautical test Range	Dryden	0	75	25
Flight Loads Research Facility	Dryden	2	8	90
0.3M Cryogenic Transonic Tunnel	Langley	40	0	60
National Transonic Facility	Langley	40	40	20
Transonic Dynamic Tunnel	Langley	7	45	48
Spin Tunnel	Langley	30	13	57
8' High Temp Structure Tunnel	Langley	0	10	90
Impact Dynamic Facility	Langley	10	20	70
Landing Loads & Traction Facility	Langley	10	45	45
Aircraft Noise Reduction Lab	Langley	30	0	70
High Pressure/Temp Facility	Lewis	0	0	100
8 × 6 Trans/Supersonic Tunnel	Lewis	55	0	45
Icing Research Tunnel	Lewis	28	30	42

NASA's "direct support" role goes far beyond providing facilities. NASA provides services (in the form of test support, instrumentation, and analysis) and research. As discussed in Chapter 2, as much as 40 percent of NASA's in-house work is devoted to responding to direct needs or requests from the military services. Many of NASA's own

15 Office of Science and Technology Policy, *Aeronautical Research and Technology Policy*, p. F-2.

16 NASA usage of these facilities accounted for 62%, while 26% was devoted to direct support of military development, and 12% to proprietary civil projects.

programs indirectly support the military, and NASA conducts many joint programs. A similar situation exists with the Federal Aviation Administration (FAA) or the Environmental Protection Agency, where NASA either performs work directly at the request of the agency (for example, in measuring wake vortex patterns of large jets for the FAA), acts as a contractor for the agency (administering quiet-propeller research for the EPA), or works as a partner in a joint program (in the NASA/FAA crash-test program).

What I have defined above as NASA's third basic mission in aeronautics is probably its most famous: generating new technological opportunities through the conduct of fundamental research in aeronautics. Examples of this role abound, from the development of supercritical airfoils that delay the onset of transonic drag rise to computational techniques that are supplementing or replacing wind tunnels. This research is typically long-term and high risk. As we shall see in Chapter 2, however, it is not as unfocused as it is often portrayed. Much of NASA's work is not "basic research" in the sense that NSF defines it, rather it is semi-focused applied science research. It has a heavy component of engineering research.

NASA's very success in technology generation has led to a fourth role, whereby NASA becomes the governmental agency for actually applying new knowledge to the solution of perceived societal problems. This role is not particularly new, since NASA and NACA have been assisting the military services with solving development problems for years (particularly during World War II). During the 1960s and 1970s, however, NASA became more actively involved in civil aviation and this role expanded dramatically. Noise reduction, the supersonic transport, short-takeoff aircraft, and energy efficiency are among the examples that will be detailed in Chapter 3. It is characteristic of this type of problem that the solutions are often only partially available through research and development. Important economic and political consequences must be addressed that frequently fall outside NASA's experience or expertise. In meeting this mission NASA needs to coordinate with other sectors of the government, with the private sector, or with foreign governments.

There are obvious possibilities for tension between these various missions. The first two missions, for example, are those of a service agency, responding to the needs of its outside clients. The third mission requires that NASA do more than merely respond; it must anticipate needs before its clients do, and thus, it must have mechanisms for independently understanding and evaluating its client's needs. The fourth mission requires that NASA act decisively--sometimes alone, sometimes in coordination as a partner.

Servant, partner, leader--these are very different roles and it seems unlikely that a single agency could do all three equally well, especially without explicitly addressing the issue.

This conflict has been recognized before, but is rarely addressed specifically.[17] The conflict cannot be resolved satisfactorily by the mission-oriented approach alone. Like the stage-of-research model, the mission-oriented model raises questions that it cannot answer. To answer these questions, it is necessary to take a step back and ask more fundamental questions of why the government is involved in R&D at all and what it is trying to achieve.

1.3 A MOTIVATION-ORIENTED APPROACH

The United States has not chosen, as have many nations, to maintain directly subsidized or nationalized aircraft manufacturers or airlines. As in its economy in general, the United States maintains a relatively clear distinction between public and private enterprises, relying predominantly on market forces to govern the economy with the government intervening to correct various failures or deficiencies. In its simplest form, the decision of whether the public sector or the private sector should undertake a given activity may be represented by the matrix in Figure 1-3. Each sector independently considers whether or not a given program makes sense (the criteria used in these decisions will be extensively discussed in later chapters) and makes a decision of whether or not to proceed. The options range from both sectors participating to neither.

		Is public-sector investment justified?	
		Yes	No
Is private-sector investment justified?	Yes	Both: Separate or joint	Private-sector program
	No	Public-sector program	No program

Figure 1-3. A highly schematized decision matrix for public versus private investment.

[17] The 1980 report by the General Accounting Office, *A Look At NASA's Aircraft Energy Efficiency Program* (PSAO-80-50), called on NASA and OSTP to formulate an aeronautical policy statement that would "give special attention to the conflicting pressures on NASA to do more basic, long term work and more focused, short-term work at the same time" (p. iii).

Obviously, the public and private sectors are not monolithic and they do not make decisions independently. For example, consider the area of aircraft energy efficiency. Cost-benefit calculations conducted by either the government or an aircraft manufacturer are likely to suggest to each of them that energy efficiency is an area worthy of research and development.[18] Despite this, some would argue that since private incentives exist, any government involvement would violate the principles of the free market and thus be inefficient.[19] On the other hand, the obvious advantage to the government of such research, and the resulting possibility that government investment may be forthcoming, may tend to discourage private sector investment. The paradoxical result can be that even in areas where both public and private sectors have incentives to invest, neither may.[20]

Even if independent actions are desired by both parties, they are not always possible. For example, the government may wish to reduce aircraft noise, but it must depend on the private sector for implementation of a noise-reduction program. Similarly, airlines may wish to reduce fuel costs through more effective routing or scheduling, but they must depend on the government for modifications to the air traffic control system. The government has so thoroughly regulated and preempted the field of aviation that independent actions are, in many cases, impossible.

Finally, it is possible that in areas where neither sector has a *prima facie* case for investment, they may find that when working together the program becomes economically attractive. This occurs when the costs are common, and thus shareable, while the benefits are distinct and separable. Chapter 5 will show that this was the case in STOL aircraft in the late 1960s and early 1970s.

Thus, in all four cases in Figure 1-3, joint public-private programs may be advantageous. Adding this consideration produces the decision tree shown in Figure 1-4.

Eight cases must now be considered. In the first, both the public and private sectors would independently decide that an activity is worth pursuing. If joint action is required (and "required" is used to mean here either *institutional* reasons, such as

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18 The airlines could reduce their fuel costs through increased efficiency, while the government would benefit from reduced fuel costs for its military transports and from reduced dependence on imported oil. A full discussion of this issue is contained in Chapter 5.

19 This is the argument made by Richard Speier in Eugene McAllister's *Agenda for Progress* (Heritage Foundation, 1980), p. 75.

20 This, of course, is the classic example of the Prisoner's Dilemma.

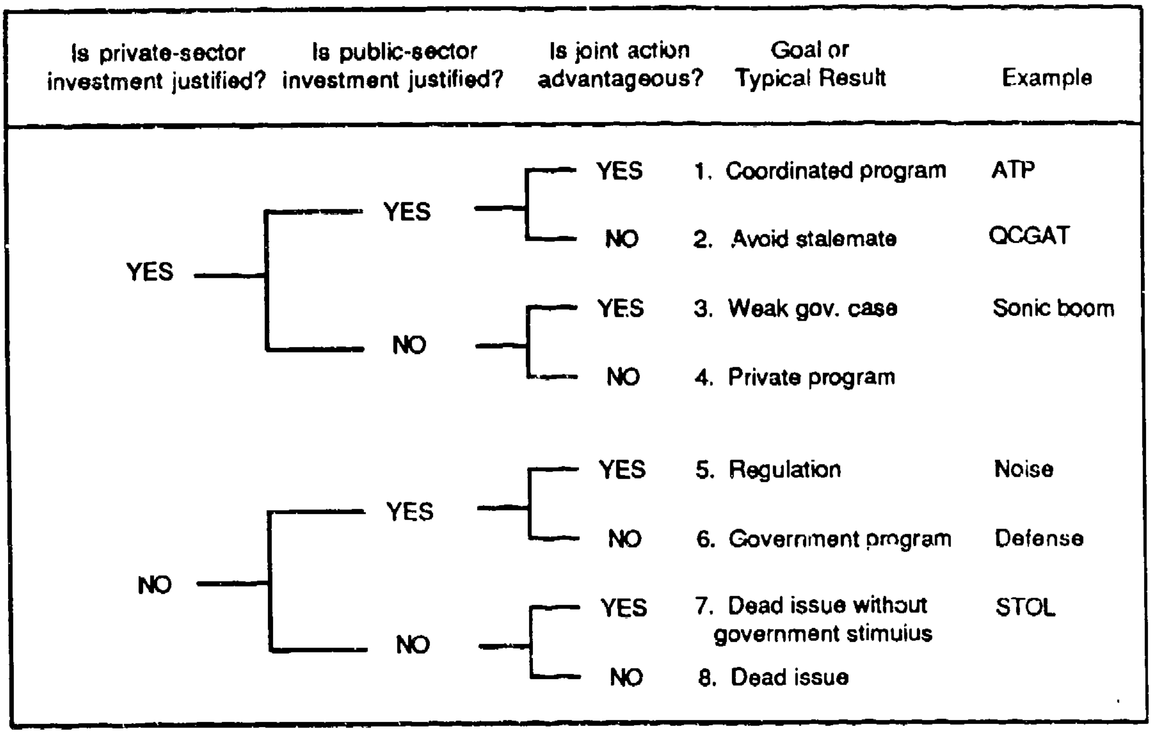

Figure 1-4. Decision tree that results when consideration about joint ventures is included.

government preemption through regulation, or *economic* reasons, i.e., the cost-benefit ratios are low or negative if assessed individually but high when considered together) then a preliminary case exists for a coordinated program. If a joint program is not required (Case #2) then the government's first interest is to avoid a stalemate. The government may decide to pursue a parallel program (perhaps to speed up development or diffusion rates), but its first priority is to avoid displacing the private sector.

In the third case the private sector has incentives to pursue a course of action unilaterally, but is blocked by some requirement for Federal action. An example might be if a private company wanted to conduct sonic boom research, which is currently prohibited overland by civil aircraft. In Case #4 no such government roadblocks exist and the private sector acts alone (this may be considered the default case in the market economy).

In the fifth and sixth cases, the private sector has neutral or negative incentives to undertake an activity while the government's incentives are positive. In cases such as aircraft noise, some cooperation by the private sector is needed, and regulation is frequently required. In cases where active implementation by the private sector is not required, the government may undertake a program by itself. The primary example of such unilateral government action is in national defense. The private sector is, of course, actively involved, but only because the government has elected to procure equipment from private firms for reasons of efficiency (indeed, for many years, defense procurement was handled through a government arsenal system).

Case #7 is among the most interesting, since neither the private nor the public sectors have adequate incentives to pursue an activity independently but a joint program can be designed to reverse this. This sometimes occurs when costs are common and shareable but benefits are distinct and appropriable. The development of short take-off and landing aircraft will be seen to be an example of such a case. In the final case (#8), neither public, private, nor joint analyses show any likely return, and an activity is not undertaken.

These eight cases now collapse generally into four categories. The first category may be considered that of the undisturbed free market (Cases #4 and #8). No government action is justified and none is required; private sector decides whether or not to undertake an activity on its own. I will refer to this case as *aeronautical R&D in a free market economy*. As will be seen in Chapter 4, it is rarely an applicable model for aeronautics.

The second category includes all those cases where the private sector has some economic incentives but the government intervenes anyway (Cases #1, #2, sometimes #3, and #7). I will refer to this category as *government-sponsored aeronautical R&D with perceived private sector benefits*. It is one of the most important cases, and will be discussed in Chapter 5.

The third category is that where public and private incentives are opposite, but joint activity is required. This usually involves regulation: either in Case #5, where government regulation may be required to influence the private sector, or in Case #3, where existing regulations may stand in the way of private sector activities. This is the case of *R&D involving regulation*, and is discussed in Chapter 6.

The fourth category is that where the government's incentives are positive and private sector participation is neither justified nor required (Case #6). The primary example is that of weapons systems, hence this category is termed *R&D for national security*. It is discussed in Chapter 7.

One of the primary distortions to a free market in aeronautics is the international nature of the marketplace and the fact that many foreign countries subsidize all aspects of their aeronautics industry. Although theoretically this is an example of government R&D in an area where the private sector already has perceived incentives, in practice this area is large enough to require discussion in a separate chapter. Thus, Chapter 8 is devoted to *aeronautical R&D for international competition and cooperation.*

1.4 CONCLUSIONS

This chapter has introduced three basic approaches for analyzing the government's role in aeronautical R&D. By far the most common approach is the stage-of-research model. Despite its many advantages and the virtual necessity for using it to actually manage R&D programs, this approach poses a fundamental policy question (how far down the spectrum should the government properly go?) that it cannot answer.

Similarly, the mission-oriented approach offers many advantages for oversight reviews aimed at ensuring that NASA meets its basic charter, but it poses a basic policy question that it cannot answer. This model serves to highlight the tension between conflicting roles NASA is called on to play, particularly the stresses between performing long-term, high risk research on the one hand and applying the results of that research to solve near-term societal problems on the other.

To answer the questions posed by the first two models, it is necessary to develop a third approach, referred to here as the motivation-oriented analysis approach. A simple decision-tree analysis suggests that there are four basic circumstances where government intervention in a predominantly market-oriented economy may be justified. Whether these circumstances actually exist in aeronautics, and whether government intervention is actually effective in these cases is the primary topic for succeeding chapters.

Discussion of these circumstances is much more realistic if it takes place in the context of actual programs. The next two chapters provide this context. Chapter 2 adopts an overview approach, summarizing broad trends in the NASA program during the past twenty-five years. Chapter 3 then provides detail on three more focused case studies.

CHAPTER 2. OVERVIEW OF THE NASA AERONAUTICS PROGRAM

In comparison to the NASA space program, which has been built around a series of development efforts with clearly defined, mission-oriented goals, the NASA effort in aeronautics has been diffuse. Both the resources that have been input and the results that have been output defy simple categorization. This chapter presents a broad summary of the NASA aeronautics program during its first quarter-century.

Figure 2-1 plots the funding of the NASA aeronautics program.[21] Between 1958, the year it was established, and 1983 the agency spent about $8.3 billion ($12.4 billion in constant FY82 dollars) on aeronautics, about 6.2 percent of the total NASA budget. This quarter-century period can be conveniently divided into three phases. The first was a period of transition, characterized by a decline in funding that extended through approximately 1963. During the second phase, between 1963 and about 1970, the aeronautics program underwent rapid and steady expansion. Since 1970 the program has remained at a roughly constant level in real terms, although there have been several significant oscillations.

2.1 THE NACA INHERITANCE

NASA did not begin with a clean slate: it inherited its initial program from its predecessor, the National Advisory Committee for Aeronautics (NACA). A full analysis of NACA and its contributions is beyond the scope of this chapter, but NACA is so frequently cited as an example of successful R&D, and its agenda so strongly influenced the early work of NASA, that a brief description is nonetheless appropriate.[22]

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21 Since 1963, all NASA funds have been authorized by Congress in three accounts. These are presently referred to as the "Research and Program Management" account (R&PM), covering NASA's in-house employees, the "Research and Development" account, covering non-personnel costs for doing research, including all contracted work, and the "Construction of Facilities" (CoF) account, covering improvements to the NASA physical plant.

22 For an overall summary by one of the key NACA leaders, see J.C. Hunsaker, "Forty Years of Aeronautical Research," *44th Annual Report*, National Advisory Committee for Aeronautics, 1958, pp. 3-27.

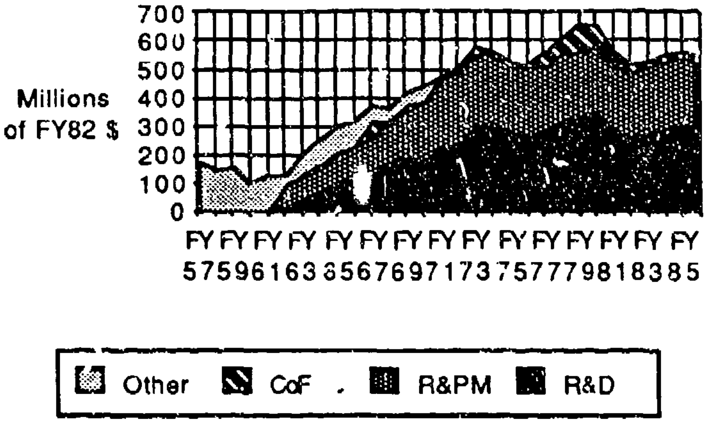

Figure 2-1. NASA aeronautics spending by fund account, in millions of 1982 dollars.
Source: NASA budgets submitted to Congress, FY61-85.

The NACA was chartered in 1915 to "supervise and direct the scientific study of the problems of flight, with a view to their practical solution."[23] Although it was formally established only as an advisory agency to coordinate the aeronautical activities of others, NACA quickly began to conduct research itself. In 1921 the Langley Memorial Laboratory was established in Hampton, Virginia, with additional centers established in Sunnyvale, California; Cleveland, Ohio; and Edwards, California, in 1939, 1941, and 1947, respectively.[24] By the time it was formally abolished in 1958, NACA had over 8,000 employees and a budget of over $100 million.

One of the unique aspects of NACA was its two-tiered organizational structure. The top tier was advisory, with a 17-member[25] "Main Committee" and four technical committees each supported by four to eight technical subcommittees. The committees were staffed with unpaid representatives drawn from universities, various government agencies and the military services, and (in later years) the aerospace industry. The second tier was the professional staff that manned the research laboratories. This was headed by a Director of Aeronautical Research, with three assistant directors and the four laboratories.

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23 The enabling legislation for NACA was a rider of the Naval Appropriation Act, Public Law 271, 63rd Congress, approved March 3, 1915.

24 Frank W. Anderson, *Orders of Magnitude: A History of NACA and NASA 1915-1976* (Government Printing Office, 1976), NASA SP-4403.

25 Originally 12, increased to 15 in 1929 and 17 in 1948.

In general, the committee helped to steer the research agenda and to promote its dissemination, while the professional staff was responsible for actually planning and conducting the research.[26] During the 1950s, the research program underwent a gradual shift in emphasis away from aircraft problems towards those related to missiles and spacecraft. By the end of FY58, approximately 50 percent of the NACA research effort was focused on rockets and spacecraft.[27] Much of the aircraft work that remained was focused around high-speed flight, either transonic (as with the Whitcomb area rule), supersonic (B-70 and its compression lift concept), or hypersonic (the X-15). Short-or vertical takeoff and landing (V/STOL) received some attention, as did operating problems such as icing or aircraft noise, but even in these areas attention shifted away from effects on people to effects of high-intensity rocket noise on structures.

In the years before World War II NACA played a unique role in the national aerospace enterprise. No other organization had even a fraction of its research capability in terms of staff, facilities, or budget, and NACA was the preeminent American institution for conducting aeronautical research and for providing advice and guidance on aeronautical issues. This changed as a result of the second World War. In the post war period NACA shared its roles not only with private companies, whose capabilities had grown vastly as a result of the war, but also with the newly independent Air Force, which established its own scientific advisory mechanism (the Scientific Advisory Board) and its own laboratory structure (most notably, the Arnold Engineering Development Center).[28]

A 1946 interagency agreement explicitly defined NACA's responsibility as "conducting fundamental research in the aeronautical sciences." Industry, meanwhile, was responsible for "the application of research results in the design and development of improved aircraft and equipment, both civil and military." The military services would focus on engineering development issues, evaluate new military aircraft, and explore possible military applications of NACA research results, while the Civil Aeronautics Authority would "expedite the practical use in civil aeronautics of newly developed aircraft and equipment, insofar as Government assistance may be necessary."[29]

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26 For an inside view of the NACA research process, see John V. Becker, *The High-Speed Frontier, Case Histories of 4 NACA Programs 1920-1950.* (NASA SP-445, 1980).

27 James H. Doolittle, "The Following Years, 1955-58," in *44th Annual Report*, NACA, 1958, p. 30.

28 For an interpretive (and controversial) organizational history of NACA, see Alex Roland, *Model Research* (NASA SP-4103, Vol. I & II) 1985.

29 See National Aeronautical Research Policy, Approved March 21, 1946.

Although the 1946 policy statement served primarily to codify existing arrangements, it accurately described the broad divisions of responsibility that have continued to be the operative model for NASA/DoD/Industry relations even up to the present time. The process it describes is a serial process that portrayed research and development as a series of ordered, progressive steps that can be divided by the type of research (basic, applied, etc.) as well as by its application.

Three additional points about NACA deserve mention here. The first is that NACA conducted its work almost entirely in-house; that is, very little of its work was contracted out. In the early years this was no doubt due to the fact that NACA was unique in its capabilities, but it is clear that NACA did not view part of its role as building up a national R&D capability outside its own labs. Even in 1955, less than 2 percent of the budget was for contract research.[30]

The second point is that NACA's most important "customers" were the military services. Although NACA assiduously maintained institutional independence, it depended on the endorsement of the military services for its continued appropriations. Although many of its developments yielded important benefits for civil aviation, and although the Committee worked in many areas of civil concern (noise reduction, crash safety, etc.), NACA never took up the explicitly promotional role for civil avaition as did the Civil Aeronautics Authority (CAA), Post Office, or even the Guggenheim Fund.

The third point is that NACA prided itself on political independence. It was widely believed within the scientific community that NACA's committee structure, with its part-time, largely non-government membership, served as a buffer between the research laboratories and the politics of Washington. This helped keep the research agenda free of political influences and, thus, highly objective. While it is undoubtedly true that the NACA program was relatively free of what is now called "micro-management" by Congress or the Executive Branch, it is unclear how much of this was due to the Committee structure and how much was merely characteristic of the times. Recent historians have concluded that NACA's structure and independent status bred "political insecurity leading to conservatism, self-promotion, reliance on committees of experts, deference to clients, and undue concern for territoriality,"[31] which in fact forced NACA "to give up, in part, the very objective for

30 Arthur L. Levine, *United States Aeronautical Research Policy, 1915-1958*, Columbia University Ph.D. thesis, 1963, p. 191.

31 *Model Research*, p. xiv.

which they were avoiding political involvement."[32] Throughout its lifetime, NACA's Committee structure was viewed with suspicion and frustration by many within the Executive Branch of the government, because it hampered both accountability and responsiveness. Over the course of the NACA's existence there were repeated attempts to reform the Committee structure and make it into a more traditional line organization.[33] As long as the agency had no operational responsibilities and had relatively small budgets, the Committee structure was able to survive. The long-sought transformation from independent committee to executive agency occurred when NACA was selected as the best home for the space program, with its high national priority and the large budgets and high visibility that accompanied the advent of manned space flight.

2.2 TRANSITION AND DECLINE: 1958-1963

The National Aeronautics and Space Administration (NASA) was created by Congress on July 29, 1958 and began operations on October 1. Earlier that year, the Eisenhower Administration had decided that the increased level of activity in space exploration deemed appropriate in the wake of Sputnik should be administered by a civilian agency, and that the National Advisory Committee for Aeronautics (NACA) should serve as the foundation of the new agency.[34] At the time of the transition, NACA had approximately 8,000 employees in four major field research centers and a budget of some $100 million. To NACA was added the Vanguard satellite program, parts of the Department of Defense's Advanced Research Projects Agency (including the Jet Propulsion Laboratory), several Air Force rocket engine programs, and a variety of smaller offices from the Naval Research Laboratory. NASA's budget (see Figure 2-2) grew rapidly as the Eisenhower Administration approved the manned orbital Mercury program.

When it became clear that NACA would likely form the core around which a new space agency would be built, an internal NACA committee was convened to study possible organizational changes. Headed by Ira Abbott, the Ad Hoc Committee on NASA Organization recommended that the new agency be headed by an Administrator and four Associate Administrators, covering Management, Aeronautical and Space Research, Space

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32 *U.S. Aeronautical Research Policy*, p. 243.

33 *Model Research*, pp. 301-302.

34 For a first-hand account of the turmoil surrounding this decision by one of its principal participants, see James Killian, *Sputnik, Scientists, and Eisenhower* (MIT Press, Cambridge, MA).

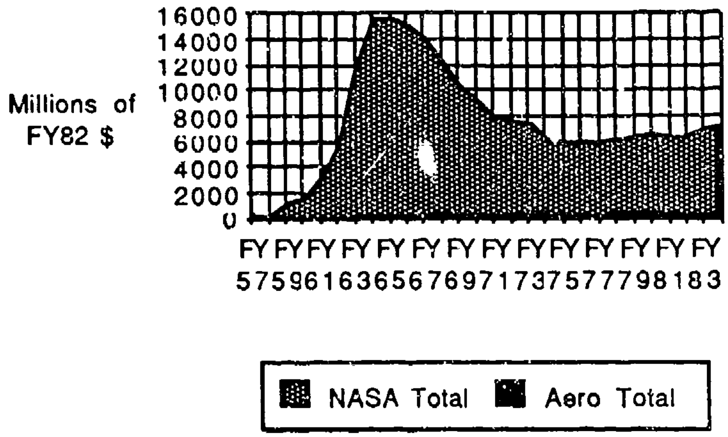

Figure 2-2. Funding history of NASA, with appropriations shown in constant FY82 dollars. The portion devoted to aeronautics is barely visible in solid black along the bottom of the chart.

Flight Programs, and Space Science.[35] Although the Space Science and Space Flight offices were combined in NASA's first organization chart, the concept of a dedicated research office endured. NASA's first organization chart had an Office for Aeronautical and Space Research (OASR) with a director, three assistant directors (to cover aerodynamics and flight mechanics, power plants, and structures, materials, and aircraft operating problems), and an Office for University Research. The four NACA research centers (Langley, Ames, Lewis, and Flight Research Center) reported to the director of OASR. In effect, the NACA committee structure had been abolished, and the aeronautics line organization had been transferred intact to NASA and shifted down one level on the organization chart.

John W. Crowley, NACA's second in command for research, was appointed as OASR's first director (see Table 2-1). In December 1959, OASR became the Office of Advanced Research Programs (OARP), apparently to standardize nomenclature with the other divisions, which were reorganized after NASA absorbed the Army Ballistic Missile Agency.[36] Ira H. Abbott, another senior NACA researcher and an assistant to Crowley, took over as Director. In 1961 President Kennedy launched the Apollo moon-landing

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35 See R.L. Rosholt, *An Administrative History of NASA. 1958-1963.* Washington: Government Printing Office, 1966. NASA SP-4101, p. 30.

36 *An Administrative History of NASA*, p. 116.

Table 2-I. Leaders of the NASA Aeronautics Program

Year	Associate Administrator†	Dept AA*	Direct Reporting on Aero**
1958	John W. Crowley	n/a	3
1959	John W. Crowley	n/a	3
1960	Ira H. Abbott	n/a	3
1961	Ira H. Abbott	n/a	3
1962	Raymond L. Bisplinghoff	n/a	John Stack
1963	Raymond L. Bisplinghoff	n/a	Charles H. Zimmerman
1964	Raymond L. Bisplinghoff	n/a	Albert J. Evans
1965	Raymond L. Bisplinghoff	n/a	Charles W. Harper
1966	Mac C. Adams	n/a	Charles W. Harper
1967	Mac C. Adams	n/a	Charles W. Harper
1968	Mac C. Adams	Charles W. Harper	Albert J. Evans
1969	James M. Beggs	Charles W. Harper	Albert J. Evans
1970	Oran J. Nicks	Charles W. Harper	Albert J. Evans
1971	Roy P. Jackson	Neil A. Armstrong	6
1972	Roy P. Jackson	n/a	8
1973	Roy P. Jackson	n/a	10
1974	Edwin C. Kilgore	n/a	12
1975	Alan M. Lovelace	n/a	8
1976	Alan M. Lovelace	n/a	8
1977	James J. Kramer	n/a	8
1978	James J. Kramer	n/a	William S. Aiken
1979	James J. Kramer	n/a	William S. Aiken
1980	Walter B. Olstad	n/a	William S. Aiken
1981	Walter B. Olstad	n/a	William S. Aiken
1982	Jack L. Kerrebrock	n/a	William S. Aiken
1983	Jack L. Kerrebrock	n/a	William S. Aiken
1984	John J. Martin	n/a	William S. Aiken
1985	Raymond S. Colladay	n/a	Cecil C. Rosen

† or senior official reporting to Administrator.
* Deputy Associate Administrator specifically responsible for aeronautics, where applicable.
** Number of officials reporting directly to AA or DAA, or name when a single individual is identifiable.

program, prompting another large round of agency expansion. In November, 1961 NASA was reorganized again and OARP became the Office of Advanced Research and Technology (OART). The old NACA structure was finally swept away, and seven new divisions were created to cover Aeronautical Research, Nuclear Systems, Propulsion and Power Generation, Program Review, Space Vehicles, Electronics & Control, and Research.[37] Raymond L. Bisplinghoff became OART Director, and John Stack, winner of two Collier trophies, was appointed to head the aeronautics division. Even though the reorganization merely codified shifts in priority that had already taken place, the net effect was to shift aeronautics down an additional notch in the NASA hierarchy. According to associates, Stack was a vigorous leader who attempted to use his contacts and influence to revitalize the aeronautics program, but personality clashes led to his departure after only about six months.

The declining priority of aeronautics was reflected fiscally as well as organizationally. As Figure 2-3 shows, NASA's emphasis was increasingly focused on space. Funds devoted to aeronautics dropped in both percentages and in real terms, from $60 million in 1958 to a low of $31 million in 1963.

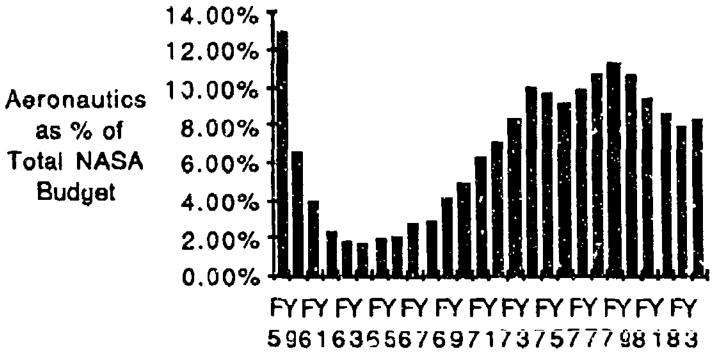

Figure 2-3. Aeronautics funding as a percentage of the overall NASA budget. During the first 25 years, spending averaged about 6 percent of the agency budget. Source: compiled from NASA's annual budget submissions to Congress and from *Chronological History, Fiscal Years 1959-1984 Budget Submissions*, NASA Comptroller, August 1983.

37 *Ibid.*, p. 224.

NASA's priorities in aeronautics during this period reflected those of NACA. Early presentations to Congress focused on four areas, including: [38]

Hypersonics, where emphasis was placed on the flight research program of the X-15 and supporting the development of the X-20 Dyna-Soar;

Supersonic Transports, where the government initiative to build a supersonic transport grew out of a series of tests at Langley. Between 1956 and 1964 NASA estimated it spent $84 million on supersonic research;[39]

Advanced military aircraft, where NASA concentrated on the development of concepts such as the variable geometry "swing-wing" later used in the F-111(TFX), F-14, and B-1, and;

Vertical Takeoff and Landing (VTOL) concepts, where NASA supported a series of triservice experimental aircraft exploring vectored thrusts, lift fans, and tilting wings.

Together, these four areas absorbed more than 80 percent of the $37.8 million budgeted for "Aircraft and Missile Technology" in 1961.[40] All of these programs shared certain common characteristics. First, in each area NASA conducted most of its research using its in-house staff. There was little reliance during this period on outside contractors, or even on university research. Second, NASA focused its efforts almost exclusively on technical issues without attempting to examine broader context such as economic or environmental impacts of the research. Third, NASA participated in interagency consortia as a supporting member rather than as a leader. Although NASA often developed the particular concept, it depended on the leadership of another agency to move the concept into flight hardware, as with the Air Force on the X-15 and X-20, the FAA on the supersonic transport, or the Army with the various VTOL aircraft. In all of these respects, the early OART aeronautics program resembled its NACA predecessor more than it did the NASA space programs. The primary force driving early NASA aeronautics policy thus appears to be inertia from the NACA.

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38 Testimony of Milton B. Ames, Deputy Director for OARP, at Authorization Hearings for Fiscal Year 1962, March 1961.

39 *Policy Planning for Aeronautical Research and Development*, Senate Document #90, May 19, 1966, p. 715.

40 NASA Budget Estimates for FY63, p. RDO 22-1.

Throughout NASA's history, observers have speculated about whether space research grew at the expense of aeronautics. Clearly this was the case during the early period discussed here. Some of it was inevitable: space was the growth field, and many of NASA's most talented and experienced researchers and managers, whose careers were based in aeronautics, were drawn into the space effort. NACA veterans such as Abe Silverstein sought to have development projects assigned to the older centers as a means of stimulating research;[41] inevitably these new development projects were in space, not aeronautics. This trend was accentuated by policies of Administrator James Webb, who sought to keep NASA out of involvements (such as the SST) that might detract from accomplishment of its primary lunar landing goal. Many in the aeronautics program itself expressed the view that most of the really valuable work had been accomplished in aeronautics, and saw the progression from aeronautics to space as absolutely logical progression, rather than a trade-off or compromise.[42] Whether official testimony before Congress represented genuine beliefs or just rationalization, it is clear that many in NASA felt a de-emphasis on aeronautics was not harmful to the national interest.

2.3 REVITALIZATION: 1963-1970

By 1963 the NASA program in space was well established, and it was obvious that the aeronautics program lacked a correspondingly clear mandate. Between 1963 and 1970 the situation reversed completely: federal aeronautics R&D funding reached an all-time peak, but following the successful completion of the Apollo moon landing the space program lacked a clear mandate of where to go next. This section explores that reversal in fortunes of the aeronautics effort.

As NASA forged ahead with the space program, not everyone shared the view that aeronautics research deserved the decline in emphasis it received. As early as 1960 the House Committee on Science and Astronautics expressed its "disappointment in what appears to be a reluctance on the part of NASA...to assume management responsibility...for the SST."[43] In 1961 President-elect Kennedy appointed an Ad-Hoc Committee on Space, chaired by his Presidential Science Advisor, Jerome Weisner. Their

41 Arnold S. Levine, *Managing NASA in the Apollo Era*, NASA SP-4102, 1982, p. 164.

42 See testimony of Ira Abbott, *Contemporary and Future Aeronautical Research*, House Committee on Science and Astronautics, August 1961.

43 HR 2041, *Supersonic Air Transports*, House Committee on Science and Astronautics, 86th Congress, 2nd session, June 30, 1960, p. 23.

report accused NASA of giving aeronautics too low an organizational priority.[44] Throughout the early 1960s, Congress continued to question the adequacy of NASA's aeronautics program, focusing on the twin themes of (1) whether the U.S. position as a world leader in aeronautics was secure, and (2) what NASA was doing to protect it.[45] In 1966 the Senate Committee on Aeronautical and Space Sciences tasked the Library of Congress with surveying the adequacy of NASA's aeronautical R&D program. The resulting "Anderson Report" criticized the lack of emphasis on aeronautical research and urged that NASA should expand its aeronautics program on the model of its space programs.[46] This in turn led to a series of hearings in both the House[47] and the Senate,[48] and ultimately a mandate from Congress that NASA and the Department of Transportation jointly conduct an in-depth study of the contributions aeronautical R&D could make to the nation's civil transportation system and, specifically, the relationship between R&D spending and civil benefits.[49] The resulting Civil Aviation R&D (CARD) Study was not completed until 1971, but the impact was in the mandate for the report, rather than the results.

These outside pressures coincided with resurgence of internal interest to produce steady growth in the aeronautics budget. Alfred J. Eggers left Ames Research Center to become director of planning for OART in 1963. In 1964 he was appointed deputy associate administrator of OART, and in October 1964 he requested Charles W. Harper, Chief of the Full Scale and Systems Research Division at Ames, to become Director of the Aeronautics Division. Harper, who had been a consistent proponent of an expanded aeronautics program, agreed on condition that he would stay 18 months to help sort out and pull together the aeronautics program. What followed was the longest and most sustained increase in aeronautics funding in the history of NASA.

The revitalization was built around a philosophy known as "proof of concept." The general argument used by Eggers and Harper was that for years, NACA had provided

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44 *An Administrative History of NASA*, SP-4101, p. 186.

45 *Policy Planning for Aeronautical R&D*, Senate Document #90, May 19, 1966, p. 15.

46 *Policy Planning for Aeronautical R&D*, Senate Document #90, May 19, 1966.

47 *Hearings on Aeronautical Research and Development*, Subcommittee on Advanced Research and Technology, Committee on Science and Astronautics, U.S. House of Representatives, 90th Congress, 2nd Session, Sept./Oct, 1968.

48 *Hearings on Aeronautical Research and Development Policy*, Committee on Aeronautical and Space Sciences, U.S. Senate, 90th Congress, First Session, January 25-26 and February 27, 1967.

49 Senate Report No. 957, *Aeronautical Research and Development Policy*, January 31, 1968.

technology which the military developed and used. Once an extensive base of experience was in place from military operations, the innovations were transferred at little risk to the civil sector. This system had produced the 4-engine turboprop and the jet transports; indeed, it had led to America's preeminence in commercial aviation. But in the 1960s they saw the military and commercial requirements diverging, as evidenced by a series of new vehicle classes (including supersonic transports and STOL) that offered potential civil benefits but were not being adequately developed by the military. Industry could be counted on to conduct evolutionary research, but it was incumbent on NASA to pick up and focus on revolutionary concepts. For this, wind tunnels, simulators, and the traditional tools were necessary but not sufficient; to really understand the concepts and to give them any chance of being picked up by industry it was necessary, they argued, for NASA to operate research vehicles that could explore concepts in actual flight. The method they proposed for this was the "proof of concept" vehicle, an aircraft that was part research facility and part demonstrator.[50]

NASA had been involved with experimental aircraft all along, of course. The most famous were the high-speed X-series of the late 1940s and early 1950s (that produced a Collier trophy for NACA) and the XV-series of the early 1960s that explored VTOL concepts. But most of these projects were administered by the military, with NACA involved in testing.[51] What Harper and others envisioned was essentially an "XC" series for civil applications, with NASA having design leadership. They were careful to stress that they did not want a prototype, and that the FAA's SST program was not a model for what they were proposing.

OART began preaching the proof-of-concept gospel to anyone who would listen in about 1965, albeit at a very low key.[52] In 1966 Harper and Adams attempted to gain formal approval of the concept from Administrator James Webb. Webb rejected the idea as

50 Most of the elucidation of the proof-of-concept philosophy remains in the NASA files. In particular, see *Aeronautics Policy and Program* by Charles W. Harper, unpublished draft dated 9/2/66.

51 NASA engineers responsible for the testing, such as Woodrow Cook, viewed the military experimental aircraft as hand-me-downs, usually designed in isolation by contractors in too much of a hurry to build prototypes. Besides, they focused only on concepts of military interest; for civil concepts, not even these second-hand testbeds were available.

52 See testimony of Mac C. Adams, Authorization Hearings for FY67, March 1966, p. 475.

a formal policy, but nevertheless authorized a *de facto* move towards it.[53] The first programs were in the noise area, where proof-of-concept hardware was almost the only way NASA could produce results (and spend the sums) in the short time demanded by Congress. The Acoustic Nacelle and Quiet Engine programs (discussed in the next chapter) built demonstration hardware but did not, in general, attempt to certify it or build entire aircraft. That remained for the short takeoff and landing (STOL) and vertical takeoff and landing (VTOL) fields, where interest was spurred by the increasing congestion in the existing civil air transportation system. Shortly after Webb left NASA in 1968, the proof-of-concept movement was institutionalized with the founding of the V/STOL Projects Office at the Ames Research Center. Its director, Woodrow L. Cook, had been attempting without success to get NASA to fund research aircraft since 1958. The office moved quickly to undertake a series of flight aircraft that included the modification of a Navy OV-10 Bronco to include the Rotating Cylinder Flap concept; this was soon followed by the Augmentor Wing, the Tilt Rotor, the Rotor Systems Research Aircraft, and the Quiet STOL Research Aircraft (most of these programs are discussed in more detail in Section 2.3).

The program that developed is shown in Figure 2-4, plotted in constant 1972 dollars.[54] Much of the program growth through 1966 was attributable to the SST, where NASA played a pivotal role prior to the selection of contractors. Thereafter, V/STOL and noise research played an increasing role. NASA's more traditional research, such as direct support of the military, accounted for less than a quarter.

Supersonic and Hypersonic Aircraft. The American SST effort, though led by the FAA, originated in a series of NASA tests conducted at Langley during the late 1950s. Although the FAA was the lead agency in the program, supersonic research was a major component of the NASA program. Much of the NASA effort went into the development of the Supersonic Commercial Air Transport (SCAT) series of configuration designs, which eventually provided the basis for both contractor designs used in the

53 This fact suggests that one of the central theses in Walter McDougall's *The Heavens and the Earth* is wrong. Webb saw his job as carrying out a specific Presidential mandate, rather than the wholesale restructuring of society under technocratic leadership. McDougall's technocratic model would predict that Webb would have strongly endorsed the proof-of-concept movement, rather than opposing it.

54 Although only R&D funds are shown, the limited evidence available suggests that in-house distributions follow this fairly closely. See notes 40 and 53.

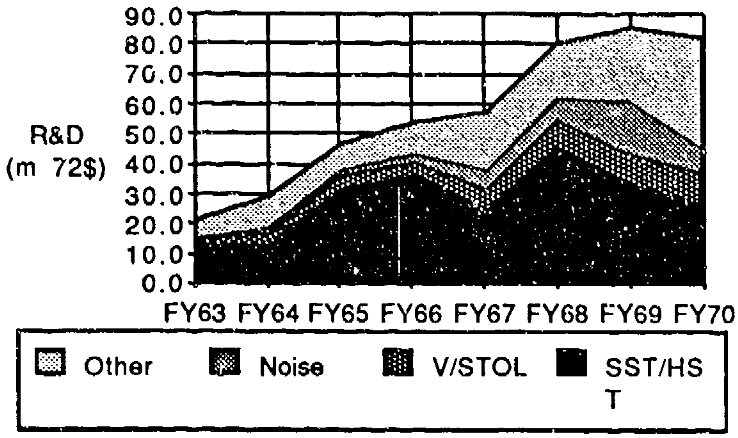

Figure 2-4. Distribution of OART R&D funding between 1963 and 1970. Funding increased in real terms more than 300 percent during this period.

development program.[55] Other NASA work studied various materials, the impact of sonic booms and jet noise, and various aircraft and traffic control systems.

Much of NASA's effort in hypersonics centered around the X-15 program, in which NASA participated as partner between 1958 and 1967, and briefly assumed full responsibility for in 1968 before terminating it due to high costs.[56] In June 1962, A.J. Evans, Chief of Propulsion and Vehicle Projects, took the first step towards an independent NASA program when he proposed that "we see the need for a hypersonic cruise aircraft to follow the X-15."[57] Although he did not present a detailed NASA program, he did have concept designs of what a vehicle might look like. The centerpiece of the hypersonics research became the Hypersonic Research Engine project (see Section 3.3), but a major effort in aerodynamics, materials, and systems studies continued throughout this period.

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55 In 1963, NASA contracted with Lockheed and Boeing to evaluate four potential designs developed by NASA. The swing-wing SCAT-16 became the basis for the eventual Boeing SST entry, while the fixed-wing SCAT-17 evolved into the double delta design used by Lockheed and eventually adopted by Boeing. See F. Edward McLean, *Supersonic Cruise Technology*, NASA SP-472 (Government Printing Office, 1985).

56 This transfer is the reason for the large jump in FY68 funding in Figure 2-4.

57 See testimony of A.J. Evans, Chief of Propulsion and Vehicle Projects, NASA, in testimony before the Senate at the NASA Authorization Hearings for FY 1963.

V/STOL. NASA continued its tradition of testing various configurations developed by others, but embarked upon a major expansion of its own efforts. In VTOL the two primary concepts were the lift-fan and the blown rotor. The lift-fan was seriously considered for a proof-of-concept program but was superseded by the tilt-rotor concept (see Section 2.4) while the blown-rotor work became the basis of an ongoing Navy research program in boundary layer control. As commercial interest increased in STOL capability, NASA launched a major program (much of it conducted in cooperation with the Canadians) to explore powered-lift concepts (see Section 3.2).

Noise Reduction. Although NACA had conducted a rather vigorous program to reduce jet engine noise in the late 1950s, NASA attention lagged considerably until it was forced by Congressional and Executive Branch pressure to take a leadership role. The origins of this pressure and the NASA response to it are described in Section 3.1. By the end of this period, NASA had embarked on two major demonstration programs: the Acoustic Nacelle Project, run by Langley, to develop acoustically lined engine nacelles that could be retrofitted onto B-707 and DC-8 aircraft, and the Quiet Engine Program, run by Lewis, to build a demonstrator engine optimized for low-noise operation.

Other Work. During this period NASA continued to play a role--providing facilities, testing, and advice to the military services, in particular following the development of the F-111 aircraft. Perhaps the best known work undertaken in this period involved supercritical airfoils, where NASA researchers took a Dutch concept for shock-free airfoils and developed it for the transonic speed range. Safety research accounted for about 2 percent of the budget;[58] it included the detection of clear air turbulence and the development of techniques for better braking on wet runways. A program of research on general aviation aircraft was instituted in 1969. Finally, in addition to a great deal of basic research oriented towards the specific areas discussed above, NASA conducted a generic research program in such areas as advanced composites (beginning in FY67) and fatigue testing.

Throughout this period, there was an increase in the use of what might be called systematic program analysis. Although NACA had always been involved in the quantitative analysis of new technologies, the NASA definition of what constituted the system grew rapidly. Factors such as cost and environmental acceptability began to be

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[58] U.S. Senate, *NASA Authorization Hearing for FY70*, Aeronautical & Space Sciences Committee, April 1969. Part 1, p. 275.

explicitly considered in trade-off studies, and for the first time NASA began to consider its vehicles in the context of a much larger transportation system. In 1965 the Mission Analysis Division (MAD) was established within OART, to institutionalize such work and feed it into the research planning process. MAD's systems studies on hypersonic transport, next-generation space launch systems, and short-haul transportation systems were complemented by contracts with numerous private companies to perform system studies. The STOL area led the way, with NASA and the FAA letting numerous systems studies beginning in 1964 and 1965. This emphasis culminated with the CARD study, intended to be nothing less than a full-blown systems analysis of the entire civil air transportation system and the roles NASA could play in improving it.

As the aeronautics program grew, it came under increasing scrutiny from Congress and other outside observers. The hearings over noise abatement demonstrated that even within NASA it was practically impossible to determine what was being spent on a specific research topic such as noise reduction.[59] Making the budget more comprehensible was thus an important priority both for purposes of internal planning and for explaining the program to Congress. In FY66 NASA began to include with its budget a "Consolidated Statement on Aeronautics" that pulled together funding from all its various accounts

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59 The confusion arose because understanding the connection between budget numbers and the level and direction of research in progress required an understanding of the overall NASA budget and the OART organization, and both of these underwent continuous evolution during the early 1960s. In FY62 and earlier, for example, there was no line item at all representing aeronautics; all the research was rolled under support for NASA's Advanced Research Centers. Beginning in Fiscal Year 1963, NASA was funded under three accounts: research and development (R&D), administrative operations (AO) and construction of facilities (CoF). In the FY63 budget, "Aircraft and Missile Technology" was broken out as a line item in the budget, and broken down by type of research: Research, Technology Development, and Flight Programs. Within each type, budget authority from all three accounts was broken down by mission (i.e., SST,V/STOL, etc.) and then by discipline (Aerodynamics, Propulsion, etc.). In 1964 only two types of research were listed, "Supporting Research and Technology" and "Projects." The SRT budget was subdivided only by discipline, while the Projects budget was divided by mission and by discipline. 1965 and later budgets used the same categories, but only "Research and Development" account funds were presented under Aeronautics. In the 1966 budget NASA included a "Consolidated Statement on the Aeronautics Program," which presented the R&D, Construction of Facilities, and Administrative Operations funding allocated to aeronautics, along with an estimate of the aeronautics contribution made by other OART divisions. This practice of issuing a consolidated statement continued through the present.

The confusion generated by this upheaval was enormous. For example, in the FY63 budget the funds proposed for SST research were $18 million dollars. In the FY64 budget, when "Supporting Research" was broken out from "Project" research, only $9 million was attributable to the SST in FY63. And in the FY65 budget, where Administrative Operations funds were not broken out, the amount specifically attributable to the SST in FY63 dropped to $2.5 million. Such variability in the budget was conducive to political manipulation but not to rational planning.

applicable to aeronautics. In 1968 the budget was brought into alignment with the organizational structure.

A third trend was the steady growth in the amount of worked contracted out. Partly, this was a reflection of the aeronautics program's need for more manpower. Because of the civil service hiring limitations and a national shortage of specialists in areas such as acoustics, NASA could not spend the large budget increases it received entirely in-house. In addition, increased interaction between NASA and the private sector was an implicit consequence of the "proof-of-concept" philosophy. Since the goal was to speed the private sector's adoption of commercially valuable technology, it was logical that industry should play a larger role in demonstration work. Finally, the management philosophy of the space program, which was to depend heavily on outside contractors in implementing NASA programs, carried over to the aeronautics side of the house. For all these reasons, there was a steady growth in outside contracting as part of the aeronautics program.

2.4 THE PLATEAU: 1970-1983

By 1970, the revitalization of the NASA aeronautics program was largely complete. Funding peaked in real terms in 1973, but then dropped back in mid-decade, peaked again in 1980, and dropped again, but the real funding level in 1983 was essentially the same as in 1971.

The NASA aeronautics organization underwent gradual but very substantial changes during this period. These began in October 1970 when OART was reorganized. The seven program divisions were reorganized and six program offices were established. The budget was streamlined into three categories covering Aeronautical Research and Technology, Space Research and Technology, and Nuclear Propulsion and Power. Finally, the name was changed to the Office of Aeronautics and Space Technology (OAST).

These changes reflected the increased importance of aeronautics, the increased emphasis on user-oriented applications, and the management style of the new Associate Administrator, Roy P. Jackson. Jackson was, by all accounts, an activist administrator who vigorously promoted new aeronautics programs and wanted to manage them all personally. Initially he coordinated the aeronautics program through Neil Armstrong (who had replaced Charles Harper as Deputy AA for Aeronautics in October 1970), but when Armstrong left Jackson abolished the position and had all the various divisions and offices report directly to him. Before his departure Jackson had over a dozen programs reporting to him in aeronautics alone. The number of independent offices began to decrease as soon as Jackson left in 1973, but the general pattern continued until 1978, when OAST was consolidated back into six divisions. Most of the aeronautics programs were centralized in the Aeronautical Systems Division, which was run by a single director, William S. Aiken, from 1978 until Aiken's retirement in 1985. Recently the number of reporting units has begun to proliferate again, with the OAST structure something of a cross between a line and a matrix organization.

The primary reporting procedure during this period was based on "Research and Technology Objectives & Plans" (RTOP) statements. Each RTOP covers a single work unit at a single center, and summarizes its goals, recent achievements, and required resources. Originally created to streamline the reporting system (500 RTOPs replaced about 4000 "Research and Technology Resumes" in 1970),[60] RTOPs continue to provide the most detailed picture available of the OAST program.

During the early 1970s, that program was driven by the concept of "relevance". The old priorities declined, as the SST was cancelled in March of 1971 and military spending turned down sharply in reaction to the Vietnam War. Guided by the results of the NAE and CARD studies, NASA's stated priorities became environmental acceptability and congestion relief within the commercial air transportation system. These translated into greatly increased programs in noise reduction and V/STOL. In 1973 the oil embargo and the resulting rapid increase in fuel prices added "energy efficiency" to the list of national priorities, and NASA responded with a major initiative to reduce aircraft fuel consumption. Later in the decade the concern became America's international economic competitiveness, and NASA launched a major program in rotorcraft, which were then experiencing severe competition from nationally-supported foreign manufacturers. As military budgets increased in the early 1980s, so did NASA's emphasis on militarily-related research.

60 See R.L. Chapman, *Project Management in NASA*, NASA SP-324, 1973, p. 41.

These shifts in emphasis are summarized in Figure 2-5, and each is briefly detailed below.[61]

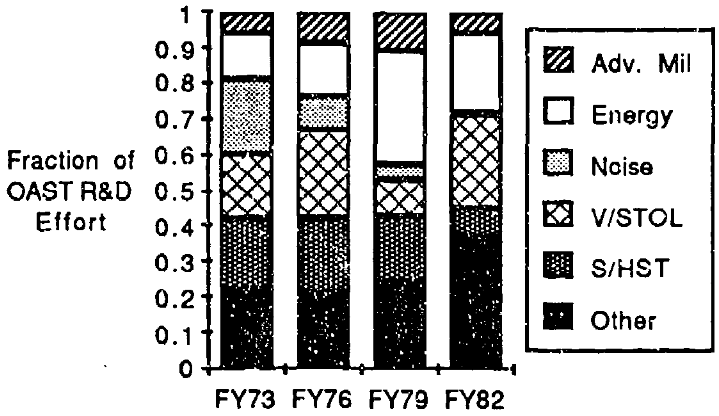

Figure 2-5. Approximate division of effort of OAST R&D account during the 1970s and early 1980s. During this period the overall level of real spending was approximately constant.

Aircraft Noise Reduction. In February 1972, noise reduction was claimed to be OAST's top priority in aeronautics.[62] NASA opened the Aircraft Noise Reduction Laboratory at Langley. Between 1971 and 1974 NASA devoted over $40 million to modify the JT-8D engine (used on 727, 737, and DC-9 aircraft) to reduce the noise and make it available for retrofit. Noise reduction was closely coupled to STOL work.

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61 The data in Figure 2-5 are the author's estimates based on a line-by-line review of the agency budget submitted to Congress, hence only funds in the R&D account are represented. In its FY76 Authorization Hearings before the Senate, NASA provided a similar breakdown based on the total program (R&D and R&PM funds). The comparison is instructive:

	R&D Account only	Overall Program (R&D + R&PM)
Advanced Military	6%	13%
Energy Efficiency	13	19
Noise & Pollution Control	21	11
V/STOL	18	17
Super/Hypersonic	20	19
Other	22	20

It is difficult to distinguish between definitional differences and actual substantive differences between content of the R&D account and the overall program. Nonetheless, it appears that the R&D account gives a fair first approximation to the overall program.

62 Testimony of Roy P. Jackson, Associate Administrator for OART, in Fiscal Year 1973 Authorization Hearings, 92nd Congress, 2nd Session, Vol. 2.

Towards the end of the decade most research in noise reduction had switched to rotor and propeller noise reduction.

Vertical and Short Takeoff and Landing. The NASA emphasis on STOL for civil applications continued into the early 1970s. In the 1972 budget NASA proposed to construct a quiet powered-lift STOL transport known as QUESTOL. When a planned cost-sharing program with industry failed, and the Air Force announced its apparently similar Advanced Medium STOL Transport (AMST), the Office of Management & Budget (OMB) killed QUESTOL in 1973. A smaller and less expensive version known as the Quiet STOL Research Aircraft (QSRA) was built and flown to test upper-surface blowing later in the decade. In addition, NASA participated in a test program with the Air Force on the latter's YC-14 and YC-15 AMST prototypes. When it became clear that commercial STOL would not materialize as soon as had once been projected, NASA cut back on its research program (this is detailed in Section 3.2). In 1978 OAST slashed STOL activity in the R&T Base, and demonstration programs such as QSRA were not replaced as planned programs were completed.

Another major component focused on advanced vertical takeoff concepts. Early in the decade extensive attention was devoted to lift-fan concepts, though no proof-of-concept aircraft was ever built. Instead, NASA and the Army teamed together to build the Tilt Rotor Research Aircraft (later designated the XV-15) and the Rotor Systems Research Aircraft (RSRA). The XV-15 led directly to the V-22 Osprey tilt-rotor currently under development for all four services after its selection as the Joint Services Advanced Vertical Lift aircraft (JVX) in December 1981. The RSRA is currently being used as the testbed for the X-wing stopped rotor concept in a joint NAVY/DARPA/NASA program.

Aircraft Energy Efficiency. Following the oil embargo in the fall of 1973, NASA began to examine ways that the fuel efficiency of aircraft could be increased. In 1975 they proposed the Aircraft Energy Efficiency (ACEE) program, with six major initiatives over a ten-year span. The ACEE brought together and enlarged NASA work on laminar flow control, composite structures, energy-efficient gas turbines (for both existing and future engines), advanced turboprops, and active controls. These elements of ACEE dominated the NASA program in the late 1970s and early 1980s, until they became targets for major cutbacks in the 1983 budget.

Supersonic and Hypersonic Research. In 1971 the SST, towards which more than a quarter of NASA's aeronautical research in the 1960s had been directed, was cancelled. Since 1967 NASA had been focusing less on the actual vehicle under construction and more on the "advanced technology," so the impact of cancellation was not nearly as severe at NASA as it was on the FAA or the contractors. What it did do was make supersonic research politically unpopular, and NASA moved quickly to distribute the components and make them less obvious in the budget. What in 1972 was called "Advanced Supersonic Technology" was concentrated under the category "long haul transport technology" in 1973.[63] Continued flight experimentation with the YF-12 was the only piece of clearly identified high-speed research. By 1976 interest in supersonics had returned on Capitol Hill, and NASA proposed the Variable Cycle Engine program to work on developing an economic, environmentally acceptable propulsion system. Other parts of the NASA program explored advanced configurations, materials, and operating conditions such as turbulence in the SST flight regime. Research in these areas continued at a low level until 1982, when both the SCR and the VCE programs were terminated.

Just as the cancellation of the SST placed a damper on continued enthusiasm for supersonic research, so the selection of the thrust-assisted orbiter shuttle (TAOS) configuration for the Space Shuttle removed a primary driver for hypersonic research. In 1973 hypersonic research was distributed between the Structures Research and Technology, Propulsion R&T, and Configuration R&T categories. In 1975, the NASA effort in hypersonics was down to about $3.8 million, and was the only integrated hypersonics effort in the nation. A joint Air Force/NASA study led briefly to the proposal in 1976 for a manned Mach 6 research aircraft, the X-24C, but no financial support was received for the project and it was terminated in 1977. Hypersonics research continued at a low level into the early 1980s, with some refurbishment work being done on the Langley high-temperature tunnel beginning in 1981. Interest in hypersonic work revived in the middle-1980s, as successors to the Space Shuttle began to be considered, and the NASA program formed the technical core around which the National Aerospace Plane (NASP) is currently being built. NASA's role in hypersonic research is investigated in more detail in Section 3.3.

Advanced Military Concepts. Many of the programs that NASA would count as "advanced military systems" have, for this presentation, already been listed under other headings (RSRA, HST, etc). In addition to those programs, however, NASA has conducted a series of programs aimed at advancing technology primarily of interest to

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[63] F. Edward McLean, *Supersonic Cruise Technology*, NASA SP-472, 1985, p. 102.

military applications. For example, in 1970 NASA configured an F-8 with a flight control computer from an Apollo spacecraft to experiment with aircraft digital flight controls ("fly-by-wire." In 1973 an F-111 fitted with a supercritical wing was flown in the Transonic Aircraft Technology (TACT) program. In 1975 a remotely piloted research vehicle was built to test advanced fighter configurations in the Highly Maneuverable Aircraft Technology (HiMAT) program. The results from HiMAT were then used in the dual-cockpit Differential Maneuvering Simulator, specifically designed to allow two pilots to fly against each other in simulators that are electronically linked together. RPVs were used again in the Drones for Aerodynamic and Structural Testing (DAST) which allowed flight experiments too dangerous for a manned aircraft. In the early 1980s OAST built the AFTI/F-16, an F-16 fitted with direct lift and sideforce controls, and the Mission Adaptive Wing, an F-111 fitted with a special variable-camber wing that replaced discrete flaps and ailerons with a smooth configured surface.

Generic Research. Although approximately half of NASA's R&D funds were labelled as covering "R&T Base," upon closer examination considerably less than a quarter of the total funds are actually for "generic" research (i.e., not attributable to a specific class of air vehicle). Included in this category is research on design methods (such as the development of the finite-element analysis program NASTRAN or the Integrated Program for Aircraft Design [IPAD]), safety, as well as what the NSF would categorize as "basic" research.[64] Although in recent years NASA has shifted more and more programs into the relative obscurity of the "R&T Base" category, the actual fraction of generic research appears to have remained relatively constant at around 25 percent of the R&D budget.

By the end of the 1970s most of the enthusiasm for government-sponsored technology demonstration programs, which had played so prominent a role in the environmental and energy areas, had waned. This was based partly on theoretical arguments (which claimed support of basic research was a more appropriate way for the government to correct market deficiencies) but also on budgetary ones: demonstration programs, in general, tended to be large and expensive relative to more basic research.

This trend manifested itself in the NASA aeronautics program by a slowdown in the ACEE program and by a decline in the number of new initiatives during the Carter

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64 In recent years, when executive office policy has been to protect "basic" research, it has often been implied that "R&T Base" and "Basic research" are synonymous. The point is made here that while basic research is an important component of the R&T Base, it is but one subpart.

Administration. It culminated, however, under Reagan in drastic cuts proposed for the FY83 budget. When the Reagan Administration entered office it declared that "any technology development...with relatively near-term commercial applications will be curtailed as an inappropriate Federal subsidy"[65] and proposed drastic reductions in federal aviation involvement across the board, ranging from funding for aeronautical R&D to support of the Export-Import Bank. Among the hardest hit were the systems technology programs previously grouped under the ACEE program.[66]

Concerned about the drastic drop in aeronautics research proposed for FY83, the congressional appropriations committees instructed the National Research Council, through NASA, to conduct an independent review of the program.[67] The Council's report, issued in July 1982, stressed the links between aeronautics research and both national defense and international commercial competition, and recommended nine of the nineteen programs excluded from the budget as having the "highest priority" for restoration.

Meanwhile, the White House Office of Science and Technology Policy was conducting its own review under the direction of Dr. George Keyworth, the President's Science Advisor. When the two-volume report[68] was released in November 1982, Keyworth announced that the six-month study had "turned up quite different conclusions than we had expected."[69] Rather than continuing to reduce funding, the Administration was urged to henceforth provide "continuing strong support for research in military and civil aviation." The primary justification for this decision was the important contribution made by NASA aeronautics to military development.

Even as the government was backing away from demonstration programs in general, however, a contrasting trend was developing that urged the government to go even further in its support of commercially plausible technology. This movement is symbolized

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65 See Office of Management and Budget, FY 83 Budget, *Special Analysis K* (Washington: Government Printing Office, 1982).

66 In the FY83 budget sent to Congress, OAST's overall aeronautics budget dropped by about 7%. This was entirely concentrated in the R&D account, which dropped 15%. Within R&D, the R&T Base was up by 15%, while Systems Technology dropped almost 70%. See NBE-83.

67 National Research Council, Committee on NASA Scientific and Technological Program Reviews; *Aeronautics Research and Technology: A Review of Proposed Reductions in the FY 1983 NASA Program.* (Washington, DC: National Academy Press, July 1982).

68 Office of Science and Technology Policy, *Aeronautical Research and Technology Policy, Vols. I and II.* Executive Office of the President, November 1982.

69 Richard Witkin, "New Reagan Policy Backs Aeronautics Work," *The New York Times*, Wednesday, November 10, 1982.

by pursuit of "industrial policy" in general and "technology validation" in particular. Driven primarily by concern over international competition, especially from foreign companies whose national governments took a vigorous role not only in R&D but also marketing and production, both aerospace industry representatives and liberal economists argued that the American government should take a more active role in promoting commercial technology.[70] In aeronautics, this emerged as an argument that it is not enough for the government to demonstrate merely technical feasibility, but the government must go on to validate the technology in operational experience. Such "technology validation" would be an important step that the U.S. could take to help American manufacturers without seriously challenging the essence of the separation between public and private concerns.

After restoring some of the proposed cuts in the NASA budget, Keyworth established an Aeronautical Policy Review Committee to provide OSTP with continuing guidance on aeronautical R&D. In March of 1985 the Committee issued a report proposing three long-range goals for subsonic, supersonic, and trans-atmospheric research. Although the report was vague in its recommendations for implementation, it did stress that "technology validation" was the most critical need in what it called the "R&D chain."[71] The report implied (but did not explicitly state) that NASA should be more involved in this aspect.

A similar conclusion was reached by a National Research Council panel studying the competitive status of the U.S. commercial aircraft industry.[72] They noted that "in light of the changing competitive environment and the technical opportunities noted in this study...we recommend reconsideration of NASA's activities and the resources available to support technology validation."

Neither those arguing for an emasculated nor those for an expanded government role in aeronautical research explicitly cite the results of NASA's previous experience as evidence to support their claims. Indeed, none of the studies seems to have bothered to formally examine in any detail the experience of the last generation. Filling that gap

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70 Spokesmen arguing along the same general line range from John Steiner of Boeing, John Newhouse of the Brookings Institution, and Robert Reich of Harvard.

71 Office of Science & Technology Policy, *National Aeronautical R&D Goals: Technology for America's Future* (Executive Office of the President, March 1985).

72 See National Research Council, *The Competitive Status of the U.S. Civil Aviation Manufacturing Industry* (Washington, DC: National Academy Press, 1985).

requires more detail than is possible in the type of broad overview presented here. It is necessary to consider specific examples through more detailed case studies. Three such case studies were conducted as part of this research and are presented in the next chapter. Before going to a more specific level of detail, we take one step further back and examine general patterns in the aeronautics program.

2.5 TRENDS AND PATTERNS IN THE AERONAUTICS PROGRAM

The previous sections have traced the evolution of OAST's budget, organization, and program. With this background it is useful to consider how the program has evolved in terms of the three analytic frameworks introduced in Chapter 1.

Any attempt to make such an analysis is immediately confronted by the lack of detail in OAST's budget, especially in funds for the in-house staff (R&PM account). R&PM funds have consistently accounted for more than 40 percent of the OAST budget, but are not detailed in any historically consistent categorization beyond the number of people assigned to a specific Center.[73] Thus, the primary guide for analyzing trends must be funding in the R&D account. The few correlations that are available suggest that the correspondence between R&PM and R&D funding is relatively good; however, there is not enough data to even quantify this correlation statistically.[74]

The stage-of-research framework. As noted in Section 1.2, OAST characterizes its research as either "Research and Technology Base" or "Systems Technology" (the names have changed several times but the idea has remained the same; also, a third category, "design studies," was used in the mid-1970s). Although these divisions do not correspond precisely with either their NSF or DoD counterparts (see Figure 1-1) they follow the same general line of reasoning. The R&T Base consists mainly

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73 This data is contained within the individual RTOPs, but its utility is limited because it is not recorded on any searchable data base. Retrieving the data requires hand searching through hundreds of microfilm records. Further, RTOPs are apparently not considered part of the Headquarters permanent record and I was unable to locate material earlier than FY74. For a discussion of RTOPs and their research utility, see Appendix 1.

74 One example (FY76) has been cited in Footnote #60. Another example is from FY63. In the FY64 budget, personnel and operating costs were included on a program-by-program basis, whereas for FY65 and succeeding years they were not. Comparing the FY63 figures as presented in the two budgets shows the correlation:

	W/personnel	W/o personnel
Supporting Research & Technology	46%	42%
X-15	24	36
Supersonic Transport	21	16
V/STOL	9	6

of work that is long-term and highly generic, what is generally called basic and applied research. The Systems Technology program is more focused on specific applications, and includes the larger "proof-of-concept" or demonstration programs. The "Design Studies" fell somewhere in-between, being more focused than R&T base activities but somewhat longer-term in orientation than most Systems Technology programs. Figure 2-6 plots the relative funding levels over the years in the OAST R&D account (as discussed above, similar data for the R&PM account are not available).

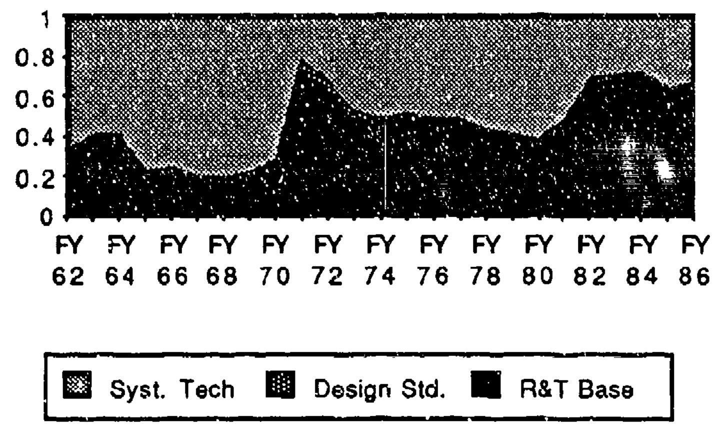

Figure 2-6. Division of emphasis between long-term (R&T Base) and short-term programs in the OAST R&D program.

The data evidently show a gradual but continuing shift from near-term experimental work to long-term, more fundamental research. This somewhat parallels the development of economic theories about technology and economic growth, which suggest that government support is most justifiable in long-term, generic research and less appropriate in near-term activities. The dramatic shifts suggested in Figure 2-6, however, are not consistent with the preceding programmatic discussion, which emphasized the role of "proof-of-concept" in the expanding NASA aeronautics program. What is going on here?

Figure 2-6 shows that large jumps in the relative size of the R&T Base occurred approximately in 1963, 1971, and 1982, followed in each case by a gradual shift back to short-term programs until the next sharp increase. Each of these discontinuities occurs at the time of a major reorganization in the aeronautics program. This suggests that at each reorganization, the agency realigns its program it bring it more in line with the prevailing economic theory, while between these realignments, the program moves gradually towards short-term applications. The fact that these realignments are less evident in the program itself than in the budget opens the question of how much of the realignment is real and how much is semantic. A precise answer is probably undeterminable; however, conversations with OAST staffers give the impression some of the realignment has indeed been cosmetic.[75]

The mission-oriented framework. It was suggested in Chapter 1 that NASA has four primary missions in aeronautics. Even though some of these missions are quite distinct, it is virtually impossible to sort out the fraction of resources devoted to each, given the structure and resolution of the OAST budget. The amount of emphasis placed on the information clearinghouse function is difficult to quantify. The amount devoted towards support of other agencies should be easier to separate in theory, but in practice it is impossible. given the lack of resolution in the R&PM budget, where interagency support is disproportionately concentrated.[76] The distinction between generating new long-term technological opportunities and developing specific technical options is, to a first approximation, the distinction between R&T Base and Systems Technology programs. Thus, Figure 2-6 with its conclusions and caveats, is as close as we can presently come to a mission-oriented breakout at the present time.

The motivation-oriented framework. The third analysis framework proposed in Chapter 1 breaks programs down by their primary policy goal; that is, whether they were justified at inception primarily by economic, regulatory, military, or national prestige considerations. Figure 2-7 is a first cut at such a division, based only on programs in the Systems Technology category (also, the "international" category is merged with "economic" for this presentation because of the high degree of overlap in actual programs). Although there are some theoretical arguments supporting this distinction (primarily, that for most basic research the results are not clearly defined enough to have a specific application in mind), the reason for making the distinction here is lack of resolution in the data for programs contained in the R&T Base. The case studies in Chapter 3 will show that many R&T Base programs are indeed generic but that many have very specific applications at the time they are initiated--but these cannot be distinguished in the budget.

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[75] An example of the type of cosmetic repackaging that can go on is given by the 1982 GAO Study, *Analysis of NASA's FY83 Budget Request for R&D to Determine the Amount that Supports DoD's Programs* (MASAD-82-33). The GAO concluded that only 1.4% of OAST's aeronautics budget was in direct support to the military, 3.7% was to support civil technologies, and 94.9% went for joint use. Obviously, different definitions were applied that those used in Figure 2-5!

[76] In FY73, for example, the OAST budget listed only $900,000 for "Technical Assistance to DoD Programs" (less than 0.5% of its total), yet more than 25% of the agency's wind tunnel time (about 16,000 hours) was devoted to direct testing for the services. See NBE-73, Vol. III, p. RD-9-22.

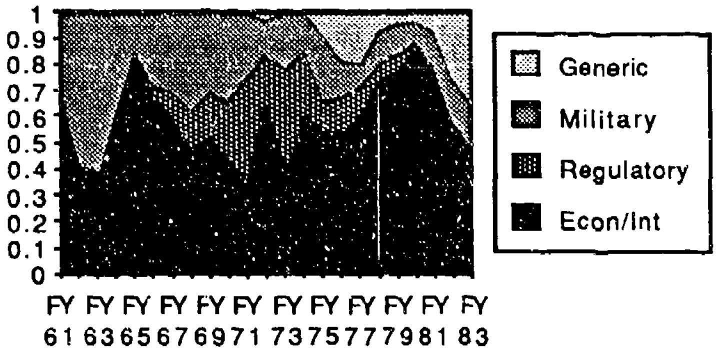

Figure 2-7. Primary motivations for short-term R&D activity by OAST.

Figure 2-7 shows that the proportion of programs undertaken for ostensibly economic considerations is very large (especially in proportion to the amount of attention given to economic analyses). The impact of the environmental movement is shown quite clearly in the increase and then decline of programs formulated specifically to support regulatory issues. The percentage of Systems Technology work in direct support of purely military concepts has declined. The fraction of Systems Technology work that is truly generic, that is, has no specific application or motivation in mind at the time it is undertaken, is very small. This is an important prerequisite for an analysis framework based on program goals and motivations.

While admittedly very tentative, the cross-cuts presented above illustrate the utility of the different analytic frameworks. By suggesting somewhat surprising conclusions, they raise important questions about how the major orientation of the program has changed over time and what exactly has been driving it. They also illustrate the difficulty in sorting out the NASA aeronautics program. Since the NASA program is devoted almost exclusively to the quantification and logical analysis of physical phenomena, it seems paradoxical that, after more than twenty-five years, the program itself cannot be quantitatively analyzed.

There are several possible explanations as to why this may be. The most obvious is the nature of the research itself. It is well established that the eventual applications are frequently unknown at the time research is undertaken. Much of the underlying technology between, say, civil and military aeronautics is quite closely related, and almost every area of NASA research has *potential* applications in many areas. Thus, it may be not only difficult but outright wrong to attempt to characterize one research program as "economically" motivated and another as "military."

Another possibility is that OAST, in an institutional example of entropy, has never been able to implement strategic planning effectively. The lower levels of NASA management have the information they need to manage on a day-to-day basis and do not need a comprehensive overview. The uppermost management levels (above OAST) devote relatively little attention to aeronautics, which represents a small fraction of overall budget. The one place in the system where comprehensive overviews might be appropriate, the Associate Administrator in charge of OAST, has been characterized by rapid turnover (see Table 2-1; the average tenure for the OAST AA is 2.2 years). Thus, the people in the best position to know or care simply are not around long enough to sort things out.

A third explanation would be that OAST has adopted the current system as a survival mechanism. The timescale of almost any aeronautics R&D program is long compared to the political attention span. Even views on large issues, such as the appropriate level of government intervention in the private sector, swing like a pendulum: from no military work to only military work; from near-term applications to only long-term research; from environmental work to no environmental research. In such an environment it may be useful, even essential, to be able to protect the substantive R&D program by portraying it in whatever light is currently favored while minimizing actual disturbances to the program.[77]

The reality probably lies somewhere in-between. Some of the people within OAST clearly believe the first proposition, that because research has many applications it is unfair to categorize or be forced to justify it based on only one. The high turnover in OAST leadership has certainly impeded the development of strategic planning, but even the Associate Administrator is not tasked with the sort of government-wide perspective for which such cross-cutting analyses are most immediately valuable. If the greatest utility for such reviews is for those outside OAST, the very complexity of the OAST program makes it virtually impossible for outsiders to develop accurately the analyses themselves. NASA's experience with outside reviews has been that the reviewers are rarely objective

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[77] Robert W. Simpson has termed this the "umbrella effect," whereby ongoing work is justified under whatever large (umbrella) program is currently politically popular. As an example, he cites the many air traffic control programs initiated under the SST that were shifted smoothly under the aegis of STOL.

(usually they are seeking excuses to cut the agency's budget) and it is not in NASA's interest to devote a great deal of effort to supplying tools that will invariably be used against them. Clearly, it is useful, even essential to NASA to be able to portray the program as different things to different people. But it would vastly overstate the Machiavellian capabilities of OAST to attribute the existing lack of analytical clarity entirely to a conscious effort.

Information of the sort that is lacking is only useful in the context of an objective analysis framework. Lacking that framework, NASA has little incentive to supply the data. This, of course, is a vicious cycle: no data, no framework--no framework, no data. This is an important issue, and one to which I will return in Chapter 9.

CHAPTER 3. THREE CASE STUDIES

Evaluating the contributions or effectiveness of the NASA aeronautical research program requires a more detailed examination than is possible in an overview such as presented in Chapter 2. This chapter presents three case studies covering NASA's research in the areas of aircraft noise reduction, short takeoff and landing (STOL) techniques, and hypersonic flight. These cases are the background upon which much of the analysis in succeeding chapters is built.

Table 3-1 lists the major NASA program areas as budgeted in aeronautics. The list suggests at least 60 possible case studies. In selecting three I sought to meet three basic criteria. The first was that, taken together, the cases should illuminate the full range of models, clients, and motivations introduced in Chapter 1. Thus, it was important to include not merely basic research but also flight and proof-of-concept experiments. The second major criterion was that each case represent an area that was essentially completed. I sought to avoid current programs partly because their long-term impact has not yet been demonstrated, and partly to avoid the political sensitivities that often accompany work in progress. Since this research is aimed specifically at assisting future decisionmaking, the third criterion was to select cases likely to be of interest again in the future.

The areas of aircraft noise reduction, powered lift technology, and hypersonic flight meet these criteria both individually and collectively. Each one involves the whole spectrum from basic research to development and flight testing. Together, they cover not only the range in vehicle performance but also the range of clients and customers served by NASA. Although each was at one time rated among the highest of NASA's priorities in aeronautics, their levels of activity during the past several years have been low, making it possible to evaluate the cases as completed programs, rather than research in progress. Finally, in each case the technology retains much of its potential, while many of the motivations for the original research remain--sure indications that each is likely to re-emerge in the future.[78]

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[78] In fact, the hypersonic issue has re-emerged during the course of this study, with proposals for the National Aerospace Plane.

Table 3-1. Major Programs in the NASA Aeronautics Budget

	A	B	C	D	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF
1	BLI	CO	UPN	Title	FY83	FY82	FY81	FY80	FY79	FY78	FY77	TQ	FY76	FY75	FY74	FY73	FY72	FY71	FY70	FY69	FY68	FY67	FY66	FY65	FY64	FY63	FY62	FY61	FY60	FY59	Totals:
2	23	762	132	Aero Propulsion R&T													6.4														6.4
3	23	763	133	Aero Operating Systems R&T													7.0														7.0
4	23	740	134	Aero Materials & Structures													11.1														11.1
5	23	750	135	Aero Guid, Cntrl, & Info Syst													3.3														3.3
6	23	760	136	Aero Vehicles R&T													19.3														19.3
7	23	770	137	Aero Life Sciences R&T													3.1														3.1
8	23	710	138	A/C Power Systems R&T													0.4														0.4
9	23	705	139	Aero Adv. Concepts & Missions																											0.0
10	23	790	363	Aero R&T Contact Admin											1.3																1.3
11	23	760	365	ILLIAC Reimbursable																											0.0
12	23	704	501	Aero R&T Base											57.0	67.7															124.7
13	23	704	504	Aero Man-Vehicle Tech									4.6	4.5	3.5																12.6
14	23	704	505	Aero R&T Base	183.0	183.9	133.7	119.1	113.6	97.8	88.8		80.6	78.8																	1059.3
15	23	702	510	Materials & Structures ST		7.6	8.7	5.0	4.5	7.1	5.3		4.2	3.3																	45.6
16	23	702	511	Propulsion ST		0.5	4.4	6.7	28.4	22.2	20.6		5.6	0.5																	89.0
17	23	702	512	Avionics & Flight Controls ST		1.3	1.2	2.2	2.4	1.7	2.6		4.6	4.3																	20.3
18	23	702	513	A/C Operating ST					8.5	7.7	9.3		12.0	11.9																	49.4
19	23	702	514	Aerodynamic Vehicle ST				0.2	4.7	3.7	8.3		7.2	2.9																	27.0
20	23	702	515	Human-Vehicle ST					0.7	0.8	0.5		0.3																		2.3
21	23	702	516	Advanced Civil A/C ST					18.9	21.0	14.0		8.8	7.6																	70.4
22	23	702	517	High-Performance A/C ST					9.0		0.7		0.9	0.8																	11.3
23	23	702	518	Rotorcraft ST					5.2	2.5																					7.7
24	23	702	530	Aero Systems Studies			3.1	4.1																							7.3
25	23	702	531	General Aviation ST			1.1	0.7																							1.8
26	23	702	532	Rotorcraft ST	32.8	30.5	23.4	23.7	23.2																						133.6
27	23	702	533	High-Speed A/C ST	20.0	7.8	16.3	14.4	14.7																						73.1
28	23	702	534	Subsonic A/C ST	17.0	27.0	32.8	57.9																							134.6
29	23	702	535	Advanced Propulsion ST	27.3	26.2	[illegible]	72.3																							172.3
30	23	702	536	Numerical Aero Simulator			0.4	2.0																							2.4
31	23	702	716	Energy Efficient Engine					43.2	18.5																					61.7
32	23	723	723	Highly Manuevering A/C Tech					0.7	2.5	6.7		4.9	1.5																	16.3
33	23	702	734	Composite Primary A/C Structures					20.4	25.2	14.9		4.0																		64.5
34	23	702	738	Quiet, Clean Short-Haul Exp. Eng					0.1	0.6	3.3		10.0	10.0	6.0																30.0
35	23	702	739	REFAN										1.0	19.6																20.5
36	23	702	741	STOL Experimental Aircraft												3.3	14.6														17.9
37	23	765	742	Advanced Transport Technology													6.7														6.7
38	23	702	743	Supersonic Cruise A/C Research						9.0	8.0		3.8	9.0	10.1																44.9
39	23	702	744	Tilt Rotor A/C Research					0.3	3.3	0.8		2.0	11.3	5.4																23.1
40	23	702	745	Rotor Systems Research A/C							1.8		3.1	8.1	5.3																18.3
41	23	702	760	Configuration R&T											18.4	22.1	13.4														53.9
42	23	760	761	Aero Vehicle Exprmtl Hrdwr													6.7														6.7
43	23	762	762	Aero Propulsion Exp Hdwr													5.9														5.9
44	23	762	764	Aero Propulsion A/C Technology													11.8														11.8
45	23	702	765	Experimental Engine Program												23.8															23.8
46	23	702	766	Flight Experiment Programs											8.4	13.9															22.3
47	23	702	767	Research/Experimental Vehicles												3.3															3.3
48	23	702	768	Operating Systems Exp Programs											14.0	11.0															25.0
49	23	702	769	Quiet Propulsive Lift Technology					1.0	1.4	1.7		10.9	8.0	12.3																35.3
50	23	705	771	Technology Applications -- Aero																											0.0
51	23	701	791	Aero Systems Studies					2.4	3.0	3.0		2.7	2.9	6.1	5.5															25.6
52	76	760	128	Aero Vehicles Supporting R&T																	18.8	10.3	11.0	8.2	7.7	3.0	0.1	1.3	4.7	2.0	70.1
53	76	760	322	ILLIAC Reimbuseable																											0.0
54	76	760	378	Aero Contract Adm. HQ																											0.0
55	76	760	719	X-15 Research Aircraft																	3.5	0.6	0.9	1.4	0.8	5.8					13.0
56	76	760	720	Supersonic A/C Technology																	12.5	13.7	11.8	21.2	5.9	4.3	0.1				69.5
57	76	760	721	V/STOL A/C Technology																	7.0	5.8	3.0	2.2	2.5	0.0					21.5
58	76	760	722	Hypersonic A/C Technology																											0.0
59	76	760	729	Hypersonic Research Engine																	7.0	6.3	1.1	2.3							16.7
60	76	760	732	XB-70 Flight Research																	10.0	11.6	0.2								21.8
61	76	760	733	A/C Noise Alleviation																	7.1	4.4									11.5
62	76	760	736	GA A/C Supporting Research																											0.0
63	76	750	737	Subsonic A/C Technology																											0.0
64	76	760	786	Advanced Studies																			0.4	0.7							1.1
65																															0.0
66				Totals	280.0	264.8	271.4	308.3	302.0	228.0	190.2	43.8	175.4	166.4	167.1	150.7	109.6	100.1	75.9	74.7	65.9	52.9	28.4	36.0	17.0	16.8	0.2	1.3	4.7	2.0	3133.4

Breakout of OAST R&D Budget
FY59-FY83
(Millions of current dollars)

Source:
FY59-68 data, NASA SP-4012
FY69-71 data NASA Budgets to Congress
FY72-83 data compiled by author
from NASA Controller's office records

3.1 AIRCRAFT NOISE REDUCTION

The introduction of commercial jet aircraft during the late 1950s led to dramatically increased noise levels around civilian airports. The resulting public concern prompted the Federal government to launch a large-scale effort to ameliorate the aircraft noise problem without constraining the growth of civil aviation. Among the primary tools used by the government were regulations and research and development. Federal R&D expenditures eventually totalled more than $500 million, with almost 85 percent spent through the aeronautics programs of the National Aeronautics and Space Administration (NASA).[79] Figure 3-1 shows the major elements of the noise case study; Table 3-2 summarizes NASA spending.

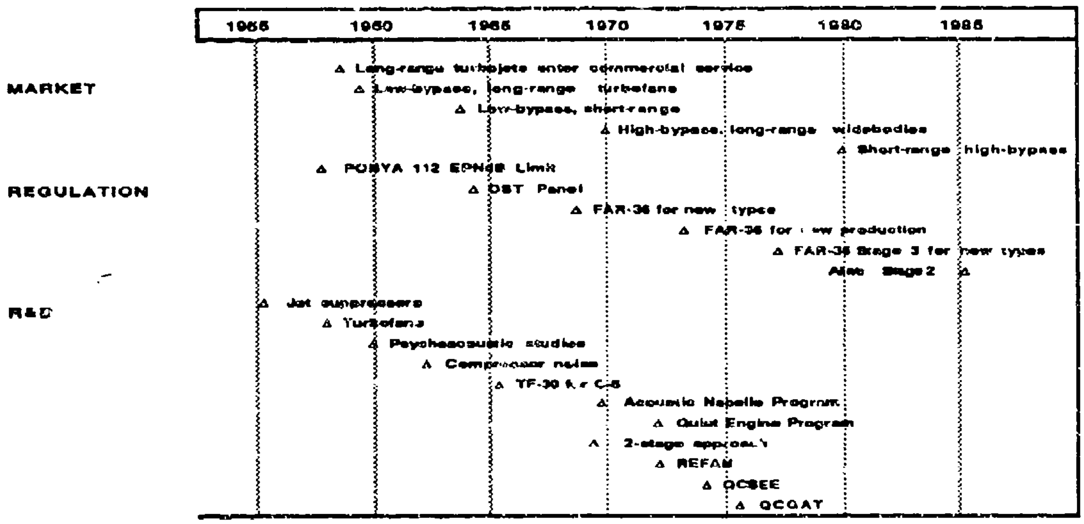

Figure 3-1. Overview of the aircraft noise reduction case showing the interrelationship between market, regulatory, and R&D events.

[79] See Federal Interagency Aviation Noise Research Panel, *Federal Research, Technology, and Demonstration Programs in Aviation Noise*, Office of Noise Abatement & Control, U.S. Environmental Protection Agency (EPA 440/9-78-307), March 1978.

Table 3-2. Identifiable NASA Spending on Aircraft Noise Reduction (millions of current dollars)

Title	FY 58	FY 59	FY 60	FY 61	FY 62	FY 63	FY 64	FY 65	FY 66	FY 67	FY 68	FY 69	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	Total
R&T Base	0.6	0.6	0.6	0.1	0.1	0.2	0.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12.0	n/a	8.2	10.0	8.5	n/a	9.0	7.7	6.2	6.6	71.3
Acoustic Nacelle										4.4	4.2	8.1	1.5												18.2
Quiet Engine											2.0	7.5	5.9	8.0	5.0	1.0									29.4
Approach Paths															0.3	2.9	3.1	1.2							7.5
QCSEE																1.8	6.0	10.0	12.0	3.3	0.6	0.1			33.8
REFAN																24.0	19.5	1.0							44.5
QSRA																	12.3	8.0	11.3	1.7	2.4	1.7			37.4
Total ($M)	0.6	0.6	0.6	0.1	0.1	0.2	0.9	0.0	0.0	4.4	6.2	15.6	7.4	8.0	17.3	29.7	49.1	30.2	31.8	5.0	12.0	9.5	6.2	6.6	242.1
Man-years:	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15	n/a	n/a	n/a	n/a	n/a	n/a	400	n/a	n/a	285	252	291	279	n/a	n/a	n/a	1522
Ref:	1	1	1	2	2	2	2	2		3	3	3	3	3,4		3	3	3	3	3	3	3	3	3	

References:
(1) HR-2229
(2) Congressional Record 5/22/64, p. 11344
(3) OAST RTOPs
(4) House of Representatives, *Aero R&D*, January 1972, p. 198.

Sources and Measurement of Aircraft Noise. Since the atmosphere has both mass and elasticity, it supports the propagation of elastic waves that the human ear perceives as sound. The ear can detect sound power levels as low as .0002 W/cm^2 and tolerate 1000 W/cm^2 before feeling pain.[80] Because of this extremely wide range, a logarithmic measuring scale (in units of decibels, or dB) has been adopted for convenience.[81] In this scale a whispered voice has a sound power level of about 40 dB, a car 75 dB, and an aircraft engine over 160 dB. The important relationship to consider is that on the logarithmic scale, a doubling of sound power produces a change of 3dB, a factor of 10 is 10dB, and a factor of 100 is 20dB.

The other important parameter for describing sound is frequency. Frequency is defined as the speed of sound divided by the wavelength; it is usually measured in cycles per second (Hertz). Pure tones contain only a single frequency, but most noises contain a mixture of frequencies and the power level may vary with frequency. For measurement purposes the frequency spectrum is often divided into bands known as octaves; the frequency doubles with each octave. The ear is normally sensitive to frequencies between about 20 and 20,000 Hz, but it is not equally sensitive in all frequencies. The nonlinearity

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80 See Cyril M. Harris, *Handbook of Noise Control*, Second Edition (New York: McGraw-Hill, 1979).

81 Power is usually referenced to a level of 10^{-12} watts, then expressed in decibels (dB) by the conversion:

$$P(dB) = 10 \log \{P(watts)/10^{-12}\} \ .$$

Thus, doubling the power is an increase of 3 dB; increasing it by a factor of ten is 10 dB. In practice, it is difficult to measure sound power levels directly so it is much more common to discuss sound in terms of pressure. Sound power is normally proportional to pressure squared, so by judicious selection of the reference level, the decibel expression of Sound Pressure Level (SPL) can be made to correlate with power:

$$SPL(dB) = 10 \log (p^2/p^2_{ref}) = 20 \log (p/p_{ref})$$

A reference level of 0.0002 microbars (0.00002 N/m2) is the standard reference in air. Note from this equation that power must increase by a factor of four for the sound pressure to double, but that both translate to an increase of 6 dB. Likewise, to reduce a sound level by 10 dB requires that the power be cut by a factor of 10 and the SPL by $\sqrt{10}$ (= 3.1).

Pressure decreases in inverse proportion to the distance from the source, so each doubling of distance produces a 6 dB drop in SPL. The correlation between power level of the source and pressure level measured at a point depends on atmospheric attentuation and reflection as well as spreading, but it can be estimated by:

$$P(dB) = SPL(db) + 20 \log r + 0.6 \text{ dB} \ .$$

Here r is the distance in feet from the point source to the measurement point. For a typical modern commercial airliner measured at the FAR-36 sideline, SPL=100 db and r=1320 feet. Thus the effective radiated power is approximately 163 dB or 20 kW. Since the aircraft engines may be producing almost 20 megawatts of total power, the percentage of total power being radiated as sound is very small. This illustrates why noise is more a concern from human factors than from aircraft efficiency, and why noise reduction so often appears to be a black art: fractional changes in the percentage of total power that is radiated as sound can have large acoustic impacts.

of a human's aural sensitivity produces problems when correlating measurements of sound power or pressure with what human test subjects perceive as "loudness." To compensate for this, a variety of procedures have been devised that essentially weight sound pressure levels as a function of frequency, so that "equivalent SPLs" can be compared without regard to frequency. The most widely used measure in aircraft noise work is the "Perceived Noise Level," expressed in PNdB.[82]

The primary effect of aircraft noise on the community is annoyance rather than physical damage. Annoyance is necessarily subjective, and tests have shown that even sounds with equal Perceived Noise Levels are not all equally annoying. Duration and tonal content have been found to be among the most important determinants (apparently the brain's neural processing system causes people to be particularly sensitive to pure tones). The "Effective Perceived Noise Level" (EPNL, measured in EPNdB) was developed as a standardized measure to include these effects.[83] EPNdB units are used by the FAA as the basis for Federal aircraft noise regulations.

To measure the cumulative impact of aircraft operations upon a community, it has been necessary to take measurements even a step beyond EPNL to what is known as "Noise Exposure." Noise exposure attempts to include such considerations as the time of day that a noise occurs and the number of repetitions within a 24-hour period.[84] On the "noise exposure forecast" (NEF) scale, levels under 30 are judged to have no appreciable noise problem. Areas with exposures between 30 and 40 experience complaints, while areas with NEFs exceeding 40 are judged to have severe noise problems. One commonly postulated goal is to reduce the area exposed to NEF levels above 30 to the size where they can be contained within airport boundaries.

It is important to note the progression in these measurements between the essentially objective SPL (used in acoustics) and the highly subjective NEF (used in psychoacoustics). At each level, the physically obtainable measurements are modified to include weighing factors based on statistical samples and subjective judgments. The

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82 PNdB was originally developed by Bolt, Baranek, and Newman during their noise studies for the Port of New York Authority in the late 1950s.

83 Starting with the PNL, an increment of up to 6.6 dB is added based on the presence of pure tones and their relative amplitudes, then a second increment is added based on the sound's duration.

84 A noise exposure calculation typically starts with flyover values for a given ground station (measured in EPNdB), adds a penalty of 10 dB for events occurring between 10 p.m. and 7 a.m., and integrates overall operations during the period.

variance of the final results is large. The subjective aspects allow for wide latitude in interpretations; this uncertainty in turn forms the basis for much of the political disagreement cited in Chapter 6.

The two primary sources of aircraft noise are the high-velocity jets and the rotating blades of the gas turbine engines.[85] Noise produced by the high-velocity jets is a very strong function of velocity, thus anything that reduces the velocity is likely to help in noise reduction. The most effective mechanism to date has been the high-bypass ratio engine, where most of the air is accelerated by a fan stage rather than by the gas generator (engine core). This gives a low average velocity, and shields the high velocity air exiting the core by surrounding it with the slower bypass air. Noise is also produced by blades moving with respect to one another--for example, compressor blades passing their accompanying stators. Noises here tend to be concentrated in discrete tones, relating to the passing frequency or its harmonics; they can be reduced by proper sizing, spacing, and numbers of blades. In addition, since blade noise originates primarily inside the engine, it can be attenuated by sound-absorbing liners built into the surrounding nacelle.

Quieting the engine itself is not the only option for reducing the aircraft noise problem. Other alternatives include shielding the noise source (usually by placing the engine behind other parts of the aircraft); increasing the distance between the source and receiver, either by moving the aircraft away from the people or by moving people away from the aircraft; or shielding the receiver (for example, by placing sound-absorbing insulation in structures on the ground). Each of these poses a different challenge and, as we shall see, has different political and economic costs. In addition, the costs of each option are borne by slightly different groups, meaning that concepts of equity must be added to considerations of economic efficiency. Finally, although the costs of noise reduction may be relatively easy to quantify, many of the benefits are difficult or impossible to quantify, making objective cost-benefit calculations difficult.

Origins of the Problem. The introduction of military jets in the late 1940s and early 1950s led to severe noise problems around military bases. Propeller noise was already a growing concern around civil airports, and the prospects of commercial jets that were as noisy as their military counterparts frightened airport operators. It was the airport operators (particularly in New York) who prompted the first real interest in reducing the

[85] Each stage of the engine process produces its own characteristic noise, but there are four basic mechanisms at work. See J.L. Kerrebrock, *Aircraft Engines and Gas Turbines*, Chapter 9.

noise of commercial jets, and who provided the manufacturers with the first quantitative design standards.[86]

The NACA had examined the question of reducing propeller noise in the 1930s and again in the late 1940s, but serious research applicable to jet aircraft did not begin until the mid-1950s. In 1952 a Presidential Commission chaired by James H. Doolittle investigating the adequacy of planning for future airport development identified aircraft noise as the problem most likely to increase in the future:

> The greatest potential nuisance is the high powered jet engine. Little is known about its noise generation mechanisms, but they are believed to be connected to power. If so, it will be extremely difficult to effect any sizeable reduction of noise without severely affecting the propulsive efficiency of the engine.[87]

In response to the Doolittle Report, NACA established a Special Subcommittee on Aircraft Noise.[88] Under its direction NACA pursued a three-phase program aimed at (1) understanding the mechanisms for generating jet noise; (2) developing devices for attenuating it; and (3) studying the impact that noise had on vehicle structures. Early commercial jet engines were direct adaptations of military engines (i.e., the J-57 became the JT-3) and were thus designed with no consideration of noise. NACA and the manufacturers placed a great deal of emphasis on jet suppression concepts, such as mixer nozzles, that could be fitted onto existing designs. The theoretical understanding was so poor that most of this work was empirical, and literally dozens of configurations were tested in the tunnels at Lewis and Langley.

The suppressors were heavy and imposed performance penalties, and they were abandoned as soon as the first turbofans became available in 1960. The JT-3D has a bypass ratio of 0.7; as the name implies it was a direct modification of the JT-3 turbojet. These engines reduced jet noise considerably, but replaced it with a high-pitched whine from the fan and compressor. The airlines switched to turbofans in droves because of the increased thrust and improved fuel consumption. Only after the engines had entered

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86 In 1954 the Port of New York Authority banned the British Comet from landing because of its high noise levels. In 1957 they set a limit of 112 PNdB for any aircraft.

87 Doolittle, J.H., et al., *The Airport and Its Neighbors: Report of the President's Airport Commission* (Washington: GPO, May 16, 1952), p. 13. It is interesting that this latter comment is technically wrong. Propulsive efficiency, $h_p=2V_0/(V_e + V_0)$, where V_0 is the speed of the aircraft and V_e is the speed of the exhaust jet. Thus, the propulsive efficiency is actually raised by lowering jet velocity, as the bypass engines were later to demonstrate.

88 See NACA Annual Report for 1955.

service was it discovered that the discrete tones of the fans were actually *more* disturbing to people below the flight path. Thus, although the early turbofans had lower sound-pressure levels than the turbojets, they actually augmented the noise problem considerably.

Widespread introduction of commercial jets. The period between 1958 and 1965 proved that commercial jet transports were soundly economic propositions, and that a true revolution in commercial aviation was here to stay. Despite early R&D efforts and the use of exhaust noise suppressors on early turbojet aircraft, however, the noise problem intensified steadily. At first it was concentrated around a handful of large, international airports served by the long-range routes. As smaller jets were introduced the problem grew to include more airports (notably including Washington, DC). Extrapolation of the growth rates seen during this period and prospect of even larger subsonic aircraft and of commercial SSTs painted a bleak picture for residents living near major airports.

The aircraft noise issue reached national prominence in the early 1960s through a series of Congressional hearings, initiated by Congressmen representing districts with large airports. Opinion was divided over the proper government role, however, with Committees responsible for the government's technical activities urging a vigorous and active program of R&D, while those Committees responsible for interstate commerce tended to view the problem as one the local governments should solve. The idea of regulation was suggested repeatedly, but in the absence of any initiatives from the Executive Branch no consensus could be formed and no legislation was forthcoming.

Preoccupied with the space program, NASA consciously limited its role in aeronautics overall and aircraft noise in particular. Noise research was reduced (it was eliminated entirely at Lewis, the center responsible for engine research)[89] and much of what remained was oriented towards acoustic effects on structures, such as those encountered in rocket development. OART's reluctance appears to have been partly a result of aeronautic's low priority in NASA overall (thus forcing noise reduction to compete with other, more traditional aeronautical pursuits), partly resistance to what was seen as a politically, rather than technically, motivated research program, and partly from concern

[89] See, for example, the letter from Floyd L. Thompson, Director of NASA-Langley, to Carl C. Austin, a patent attorney in New York, April 3, 1963: "...the NACA was at one time active in...noise suppression devices....At the present time there is no active program relating to jet engine exhaust noise suppressors at NASA." [NASA Archives]

that research alone could not solve the noise problem.[90] A combination of direct Congressional pressure plus the fear that the FAA might develop its own indigenous research capabilities caused NASA to begin expanding its noise research in 1964 and 1965, but it took a mandate from the White House before NASA significantly augmented and realigned its approach to the aircraft noise problem.

Despite the low level of NASA activity, the basis for several future solutions emerged during this period. A major advance in the understanding of compressor noise occurred in 1962, when researchers at Pratt & Whitney aircraft published the first comprehensive theory of blade noise production. Substantial reductions in jet noise were promised by the development of high bypass-ratio turbofans for the C-5A military transport. The large size and long range requirements of the C-5 placed an unprecedented premium on fuel efficiency, and led to the use of a bypass ratio (8) considered technically impossible only a few years before. The high bypass ratio led to low exhaust velocities, and reduced jet noise levels. Although the development of the General Electric TF-39 owed much to NACA/NASA technology (for example, transonic blade designs) most of the new research performed during this period was done by industry with intellectual assistance of universities and funding from the military.

First Wave of NASA Programs. In October of 1965 Dr. Donald Hornig, the President's Science Advisor and the Director of the Office of Science and Technology (OST), convened a panel of experts to assess the growing problem of noise around airports. The Ad Hoc Jet Aircraft Noise Panel included representatives from OST, the Federal Aviation Agency (FAA), NASA, several airport authorities, airlines, manufacturers, and noise specialists. The resulting report, *Alleviation of Jet Aircraft Noise Near Airports*, was issued in March 1966 and became the roadmap for future Federal activity.

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90 This attitude is perhaps most clearly expressed in a paper entitled "Discussion of Limitations to NASA Aircraft Noise Research Programs," written by William S. Aiken at NASA headquarters for the 1965 OST Study. The primary point was that "any discussion of real or implied limitations of the current and planned NASA aircraft noise reduction effort must be tempered by the continued realization that aircraft noise reduction has many broad implications. Our best technical evaluation indicates that aircraft noise can never be completely eliminated at the source but only reduced through research. It follows that research alone, at whatever accelerated pace, cannot resolve the noise problem without the complete cooperation of both the operators, through their acceptance and use of suppression techniques, and the communities, in their proper control over public exposure. *Unless such a total program can be agreed to no solution can be expected to be found through research.*" (emphasis added).

The Panel's first, and probably most significant, conclusion was that initiative for reducing aircraft noise could only come from the Federal government. The panel provided what was to become NASA's charter in the noise area: "The FAA and/or NASA, using qualified contractors as necessary, (should) establish and fund adequately an urgent program for conducting the physical, psycho-acoustical, sociological, and other research results needed to provide the basis for quantitative noise evaluation techniques which can be used....for hardware and operational specifications."[91] This charter was significant in three main respects. First, it established the primary motivation of NASA's research program as the development of and support for the technical basis for noise regulation. Second, while accepting the importance of in-house research, it switched the organizational model from that of NACA to that used by NASA for the space program. Third, it directed a broadening of NASA's sphere of interest from the purely technical to include economic and other social science pursuits.

NASA reacted to its executive office mandate by dramatically overhauling their noise research program. To move beyond basic research they established a separate R&D project for Aircraft Noise, and they began planning to acquire their own aircraft. Unable to augment internal staffs sufficiently, they turned to large-scale contracting with industry. Three major programs eventually emerged: the Acoustic Nacelle Program, headed by Langley and aimed at determining the feasibility of nacelle retrofits for existing airliners; the Quiet Engine Program, headed by Lewis, to develop a demonstrator engine optimized for low noise; and a Steep Approach program, conducted jointly by Langley, Dryden, and Ames to develop techniques and equipment for rapid descents into airports, with the goal of minimizing noise exposure on the ground.

Acoustic Nacelle Program. The Acoustically Treated Nacelle Program began in May of 1966 when NASA initiated a program to determine the technical feasibility and financial cost of retroactively quieting the noisiest segment of the aircraft fleet, the early model DC-8s and 707s through the development of special nacelles (the coverings that house the engines) that would reduce the sound radiated away from the airplane. The Douglas program focused on the development of sound-absorbing material (SAM) for reducing inlet noise on short duct nacelles on the JT-3D engine. Boeing was tasked to explore the sonically choked inlet (where the flow reaches Mach 1 and thus blocks the

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[91] OST, *Alleviation of Jet Noise*, p. 8.

upstream propagation of sound waves), as well as SAM for the exhaust duct (as opposed to inlet) lining.

The Douglas work with SAM proved so effective, and the choked inlet had so many complications,[92] that the latter was abandoned and the Boeing program redirected at fabricating a full-length nacelle of the 707's JT-3D engine. The Douglas nacelle reduced the sound pressure level during landing approach by approximately a factor of three (10.5 EPNdB), while the Boeing full-length duct provided 15.5 EPNdB.[93] As expected, reductions on sideline and takeoff (where jet noise dominated) were smaller but nonetheless significant, roughly a factor of 1.5 on each (3.0 and 3.5 dB, respectively). Both modifications added weight (332 lb to a DC-8, 3140 to a 707)[94] and reduced thrust (3 percent for Douglas); together with installation costs these penalties were estimated to raise typical airline costs between 5 percent (Douglas)[95] and 9.2 percent (Boeing).[96]

The Quiet Engine Program. Internal NASA studies had long indicated that the most effective means for reducing jet noise was the use of high bypass-ratio engines. The Quiet Engine program was conceived as a demonstration program that would optimize a modern engine for low-noise operation, and thereby demonstrate just how quiet jet engines could be. In 1969 NASA requested proposals for quiet engines sized for retrofit on the B-707 and DC-8. The two contractors who bid took opposite approaches: Pratt & Whitney proposed the design of an entirely new engine core,[97] while General Electric proposed an engine based on a derated core of its existing CF-6. A contract was awarded in July 1969 to GE for the design, construction, and preliminary testing of two quiet engines, one testing a slow-speed subsonic fan; the second with supersonic-tip fan. The nacelle for the quiet engine was based on results of the Acoustic Nacelle program

92 Since the mass flow changed with various flight conditions, it required a variable-area inlet, with obvious complexity and flight reliability problems.

93 J. Atvars, et al., "Acoustic Results of 707-320B Airplanes With Acoustically Treated Nacelles," in *Acoustically Treated Nacelle Program*, NASA SP-220.

94 R.B. McCormick, "Performance of the 707-320B Airplane With Acoustically Treated Nacelles", in NASA SP-220.

95 H.D. Whallon, "Economic Implications of Retrofitting Short-Duct DC-8 Airplanes with Acoustically Treated Nacelles," in NASA SP-220.

96 J. Fletcher, "Economic Implications of Retrofitting 707-320B Airplanes with Acoustically Treated Nacelles," in NASA SP-220.

97 Which would have cost over $50 million.

completed earlier.[98] A primary feature of nacelles was the use of three concentric rings in the inlet, all covered with sound-absorbing material.

The noise reduction demonstrated by the Quiet Engine was impressive. At takeoff thrust, the QE would have been at least a factor of 6 (16 PNdB) quieter than existing engines; on landing approach, a factor of 9 (19 PNdB).[99] Table 3-3 summarizes the results and compares them with other aircraft.

Table 3-3. Summary of Quiet Engine Results

	Takeoff	Approach (EPNdB)	
DC-8	121	118	
FAR-36	104	106	
QE A	0 95	98	(no nacelle)
QE A	0 89	93	(with nacelle)
DC-8-62	0 94	98	(CFM-56)

Modification of Approach Paths. It was recognized very early that one of the least expensive alternatives for reducing aircraft noise received on the ground was to change the flight paths so as to reduce the ground exposure. Beginning in 1967, NASA pilots flew a series of experiments designed to determine whether it was practical to double the approach angle flown by jet aircraft during approach and landing.[100] Pilots from NASA, the FAA, and commercial airlines who flew a specially modified B-707 concluded that a two-segment approach that descended at 6-degree glide slope down to 400 feet in altitude before transitioning to the standard 3-degree slope was safe and practical. Such an approach reduced noise levels by about 10 EPNdB. The pilots recommended, however, that several modifications were needed to make this system practical, including a 2-segment guidance

98 M. Dean Nelson, "Quiet Engine Nacelle Design," in *Aircraft Engine Noise Reduction*, NASA SP-311.

99 These results based on static tests, actual reductions were expected to be greater in flight. Carl C. Cieplich, "Quiet Engine Test Results," in NASA SP-311.

100 See H.C. Quigley, R.C. Innis, and E.B. Fry, "Flight Investigation of Methods for Implementing Noise Abatement Landing Approaches," in NASA SP-189, *Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft*, 1968.

system on the ground, a special flight director in the cockpit, and an auto-throttle system on the engines.

The Second Wave of NASA Programs. In 1968, Congress gave the FAA formal authority to regulate noise emissions as part of the aircraft certification process. Aided by the results of the NASA research program, the FAA promulgated Part 36 of the Federal Airworthiness Regulation (FAR-36), setting up noise standards based on weight. Initially these regulations applied only to new aircraft *types*, but they were extended in 1974 to include all new aircraft and tightened in 1977.

The creation of the Environmental Protection Agency (EPA) in 1970 added another institutional player to the policy debate over noise reduction. During the early 1970s two primary issues were dominant: first, to what degree should noise regulations be extended to cover existing aircraft, and second, should the standards be tightened for the future. These issues are treated in more detail in Section 6.1.

This debate led NASA to initiate a new wave of programs between 1973 and 1975. Like the first wave developed in the mid-1960s, these programs were intended both to provide data and options for regulatory decisions and to advance the technology of noise reduction.

REFAN. In December 1971, a proposal from the White House launched REFAN, NASA's largest and most expensive noise reduction program.[101] The original idea was to develop quiet versions of the JT-3D (powerplant for the B-707 and DC-8) and JT-8D (B-727, 737, and DC-9) engines that could be retrofit onto existing aircraft. The program was launched in January 1972, but costs of modifying both engines proved to be too high and the JT-3D modifications were dropped in favor of the JT-8D.[102] By early 1975 three development engines had been built and tested on the B-727 and the DC-9. Known as the JT-8D-109 REFAN, the original two-stage fan was replaced by a single, larger fan stage. This doubled the effective bypass ratio (from 1.05 to 2.03), reduced the effective jet velocity, and increased the thrust. The lower jet velocity reduced the takeoff noise considerably (by 10 EPNdb for the DC-9 installation), while the single-stage fan and

101 William M. Magruder, former manager of the SST program, had moved to the White House Domestic Policy Council. REFAN was proposed during the Council's New Technology Opportunities Program, and enthusiastically received by OAST AA Roy Jackson.

102 The idea was that retrofitting would be expensive, and the JT-3D aircraft would probably be retired rather than retrofit, while the JT-8D aircraft had more of their productive lives remaining.

acoustic nacelle treatment reduced the approach noise by about 6 EPNdB. Together, these modifications reduced the area exposed to 90 EPNdB by over 60 percent.[103]

QCSEE. Beginning in FY1973, NASA built and tested two research engines designed for low-noise operation on short takeoff and landing (STOL) aircraft. These Quiet Clean STOL experimental engines are discussed in Section 3.2 under powered-lift technology. The noise standards for QCSEE were among the most ambitious ever undertaken: 95 EPNdB at a 500 ft sideline station for a 150,000-pound aircraft.[104] Extrapolating this to the standard FAR-36 sideline station implies 82.5 EPNdB.

QCGAT. In 1975 NASA undertook the Quiet Clean General Aviation Turbine (QCGAT) in an effort to extend its noise- and pollution-reduction technology to smaller engines than used in previous efforts. The Garrett Turbine Engine Company and Avco-Lycoming were each contracted to design and build 5,000-pound class engines for ground testing. In addition to meeting noise goals 8 to 12 EPNdB below any existing engine in that class (and 16 to 19 EPNdB below existing standards), the QCGAT engines were intended to determine the feasibility of proposed EPA restrictions on engine emissions.[105]

The engines were successfully completed and delivered during 1979. Much of the technology represented a new application rather than new technology per se; however, substantial advances were made in mixer nozzles. These alone accounted for a 1 percent improvement in fuel consumption and 3-5 EPNdB in noise reduction on the Garrett engine.[106]

Decline of Aircraft Noise Research. The promulgation of the Stage III regulations in 1977 was the most recent major new Federal initiative in aircraft noise control. A combination of four factors seems to have pushed it off the public agenda. First, new subsonic aircraft had indeed become quieter (the relative contributions of technology versus regulation are examined in Chapter 6) and the national noise exposure had begun to decrease. Second, the supersonic transport, long a parallel issue but one latent with emotion, essentially vanished as a public issue. These factors together removed concern that things would get worse. Third, the cost of fuel increased dramatically during

103 Robert W. Schroeder, "REFAN Program," in *Aeronautical Propulsion*, NASA SP-381, May 1975.

104 Carl C. Ciepluch, "QCSEE Program," in *Aeronautical Propulsion*, SP-381.

105 Gilbert K. Sievers, "Overview of NASA QCGAT Program."

106 Roger W. Heldenbrand, *AiResearch QCGAT Engine, Airplane, and Nacelle Design Features*, NASA CP-2126.

the latter half of the 1970s, shifting national attention from the environment to energy. Finally, in the 1980s, the Reagan Administration engaged in a systematic dismantling of the environmental structure that stripped the EPA of its aircraft noise expertise just as the agency was beginning to develop a true capability.

As overall interest has decreased, the NASA research effort has shifted its emphasis and the overall level of noise research has decreased. Recent noise reduction work has focused on rotorcraft and propeller noise, especially for general aviation aircraft and for advanced turboprop engines. The overall budget for noise research has decreased dramatically.

Impact. What contributions have the various NASA programs made on reducing aircraft noise? The most obvious conclusion is that most of the NASA demonstration programs have not been utilized in the way that they were originally envisioned. The Acoustic Nacelle, for example, was not retrofitted on DC-8s or B-707s. Contrary to what is sometimes claimed, the Quiet Engine had virtually no impact on the large turbofans for the B-747, L-1011, or DC-10; by the time data from the QE was available in 1972, the commercial JT-9D, CF-6, and RB-211 were already certified and in commercial operation. The 2-segment approach has yet to be widely adopted, and the REFAN was never retrofitted onto existing aircraft. Special engines for STOL aircraft, as developed in QCSEE, have yet to be developed. QCGAT stands out as the major exception, as Garrett used the $4 million NASA program to launch a $40 million development program of its own to develop the TFE-731-5, currently one of the most successful engines for corporate aircraft.

Yet, each of these programs had a strong impact. SAM developed during Acoustic Nacelle was promptly incorporated into the nacelles of the new high-bypass turbofans used on the B-747, DC-10, and L-1011. It was fitted into new-production versions of the B-727, B-737, and DC-9 beginning in 1972, and this alone allowed them to meet FAR-36. Refinements have continued in the private sector over the years boosting the effectiveness of SAM a further 50 percent, and the new material is used extensively in new Stage 3 aircraft like the B-757, B-767, and MD-80.[107] The Quiet Engine provided much of the technology for the CFM-56 (similarly sized but built around a completely different engine

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107 Vaughn Blumenthal of Boeing said in 1973 that "Much of the original acoustic technology was developed in the NASA...program starting in 1967. That work has been invaluable in arriving at today's acoustic configurations." House Hearings, *Aircraft Noise Abatement*, December 1973, p. 142.

core); this engine has been retrofitted on a few DC-8-60 series (to produce the DC-8-70 series) and has been extremely successful as the powerplant for the B-737-300, a stretched, derivative aircraft that between 1983 and 1985 sold more than 500 copies. Despite its success in meeting noise performance goals, the JT-8D-109 REFAN was never adopted for retrofit. The FAA elected instead to promulgate rules that could be met by B-727s and DC-9s with only the much less expensive SAM material (the wisdom of this decision is strongly questioned in Chapter 6). The REFAN went on, however, to power a new generation of derivative aircraft when McDonnell-Douglas elected to use the JT-8D-209 (production version of the -109 REFAN) to power its MD-80 series of commercial transports. By 1986 Pratt & Whitney had sold more than $3 billion worth of JT-8D-200 series engines.[108]

More generally, the noise demonstration programs helped pull NASA back into the aircraft field. At Lewis Research Center, for example, the program manager for the Quiet Engine was transferred in from the defunct 260 in. solid rocket project; he had to assemble his research team from scratch. At Langley, the Noise Reduction Laboratory was slow being established, but has since its opening in 1972 provided a focal point for acoustic work in several areas, including rotorcraft and propeller noise.

Within industry, the programs helped to promote competition. The companies most eager to participate in NASA programs were generally those with the smaller market share. General Electric, for example, was attempting to reenter the commercial engine field with its CF-6. The Quiet Engine helped expand the technology base for a smaller engine, which eventually became the CFM-56. When Douglas could not afford the cost of developing a new aircraft, it adapted the JT-8D-109 REFAN to power its MD-80.

3.2 PROPULSIVE LIFT TECHNOLOGY

The requirement for long, horizontal runways has always limited the operation of heavier-than-air vehicles. Although helicopters provide vertical takeoff and landing (VTOL) capability, they are severely limited in terms of range and speed when compared to conventional takeoff and landing (CTOL) aircraft. For the past quarter-century great research emphasis has been placed on hybrid concepts that combine vertical takeoff with

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108 See "Sure Success for JT-8D," *Flight International*, February 8, 1986. Since its introduction in 1964, more than 13,000 JT-8Ds have been sold, by far the largest number of commercial engines of a given type.

efficient cruise operations. The compromises on such hybrids remain severe, however, with no single optimized vehicle in sight. For some applications vertical capability is not required; many benefits can be obtained by operating from comparatively "short" runways (variously defined between 500 and 2000 feet). To provide this short takeoff and landing (STOL) capability to large transport airplanes requires "powered lift" concepts that use part of the energy from the propulsion system to augment the aerodynamic forces during takeoff and landing, rather than merely providing forward thrust. NASA has invested approximately a quarter-billion dollars in STOL research (see Table 3-4, counts R&D plus R&PM costs).

Concepts. The need to provide aircraft with both high-speed capability for cruise and low-speed capability for takeoff and landing has spurred the development of high-lift devices that can be deployed for slow-speed flight but retracted at high speeds. The development of the mechanical flap provided significant increases in lift coefficient, and flap refinements continued through the second world war. Operational use of high-lift devices lagged laboratory development. By the late 1940s, however, much of the potential of mechanical flaps appeared to have been developed, and designers began to seek other techniques for high-lift devices.[109] One of the most attractive routes was through use of propulsion air for boundary layer control

Although there is a wide variety of specific concepts for producing powered lift, each of them relies on some combination of three basic effects. The first is the normal lift generated by an aerodynamic surface such as a wing. The second is deflection of the engine's exhaust, so that part of the thrust is used to produce direct lift. But the heart of powered lift is a third effect, that combines features of the first two: air flow produced by the propulsion system is used to modify the performance of the lifting surface, usually by injecting high-energy air into the slipstream, known as boundary layer control. Although a full discussion of BLC is beyond the scope of this paper, it will suffice to say that the performance of a wing is normally limited by its tendency to stall. Much of the lift of a wing is produced by a region of low pressure on the wing's upper surface. Since the pressure must return to atmospheric at the end of the wing, it follows that on the upper aft portion of an airfoil the air faces a region of increasing (or adverse) pressure. If there were no friction losses in the flow, the air would have just enough energy to return to

109 J.P. Campbell, "Overview of Powered-Lift Technology," in NASA SP-406, 1976.

Table 3-4. Identifiable NASA Spending on Powered-Lift STOL
(millions of current dollars)

Title	FY 63	FY 64	FY 65	FY 66	FY 67	FY 68	FY 69	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	Total
R&T Base	0.3	0.9	0.7	1.0	1.9	2.3	2.7	3.1	7.1	n/a	n/a	10.6	7.6	5.2	3.8	3.3	2.4	1.8	1.4	56.1
Aug Wing												0.6								0.6
QUESTOL										14.6	3.3									17.9
QCSEE												6.0	10.0	10.0	3.3	0.6	0.1			30.0
AMST												0.5	1.1	2.7	0.4	0.2				4.9
QPL												12.3	8.0	10.9	1.7	1.4	1.0			35.3
CSRA												3.6	3.6	7.3	1.7	0.7	4.1	2.6	1.3	30.4
Total R&D($M)	0.3	0.9	0.7	1.0	1.9	2.3	2.7	3.1	7.1	14.6	3.3	33.6	35.3	36.1	10.9	6.2	7.6	4.4	3.2	175.2
Man-years:	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	285	258	203	175	135	197	147	116	1518
Ref:	1	2	2	2	2	3	2		3	3	3	4	4	4	4	4	4	4	4	

References: (1) NASA SP-4012
(2) S-90
(3) FY 71 Authorization Hearings
(4) OAST RTOP files

atmospheric pressure, but friction losses do occur and extra energy must come from somewhere. Usually it is supplied through turbulent mixing in a thin region known as the boundary layer; this mixing increases the friction drag but does not reduce the lift. As the lift is increased the adverse pressure gradient is increased, until at some point large scale mixing ensues; the flow is separated, the lift drops dramatically, the drag increases substantially, and the wing is said to have stalled. Boundary layer control seeks to augment the wing's lift capability by selectively increasing the energy in the boundary layer to prevent separation. This can be done through a variety of techniques, such as sucking off the low-energy boundary layer (allowing its replacement by higher-energy air) or by injecting the higher-energy air. Figure 3-2 illustrates several concepts that use high-energy air produced by the engine as the basis for BLC.

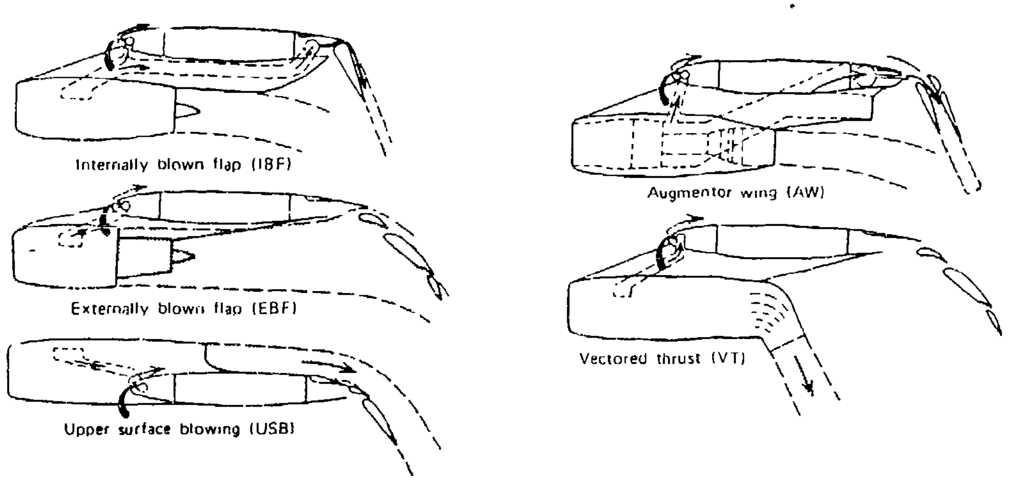

Figure 3-2. Various high-lift concepts examined in NASA research on powered lift. In each case, high energy air from the propulsion system is used for boundary layer control, significantly augmenting the wing's ability to produce lift.
Source: L.T. Goodmanson and L.B. Graetzer, *Recent Advances in Aerodynamics for Transport Aircraft*, AIAA 73-9, 1973.

The most basic concept is that of a *jet flap*, where engine air is exhausted through the trailing edge to form a "virtual" flap that both energizes and steers the surrounding flow. A similar concept is the *internally blown flap* (IBF), where a mechanical flap is used to steer the flow and air injected at the leading edge of the flap energizes the flow and prevents separation. A third concept is the *augmentor wing*, which is similar to the IBF except that a slat has been added above the flap to form an ejector nozzle; this nozzle uses the high-pressure blown air to entrain a larger portion of the boundary layer and produce thrust as well as to enhance lift. An alternate approach which involves much less internal ducting is the *externally blown flap* (EBF), where air from the engine is physically deflected by the flaps, which have been lowered into the exhaust flow. Another version of this concept is *upper surface blowing*, which takes advantage of an aerodynamic characteristic known as the "Coanda effect" (where high-speed air will follow even highly curved surfaces) and flaps to turn the flow.

Much of the early development in powered-lift took place outside the United States. Boundary layer control had been proposed in Germany in 1921, and the Jet Flap in 1932, but practical applications had to await the development of the turbojet engine in the 1950s. The jet flap was investigated extensively in England during the mid-1950s,[110] and the results prompted NACA to begin research on powered-lift concepts. Two important variations of the jet flap, upper-surface blowing and the externally-blown flap, were under investigation by NACA at the time NASA was created in 1958.[111]

Early NASA Work. NASA's interest in STOL can be considered in four approximate phases. The first began with the agency's formation in 1958 and lasted until approximately 1965. During this period NASA more or less continued NACA's focus on VTOL for military applications, with STOL concepts tested as opportunities arose. By 1965 NASA began to focus more on powered-lift STOL for civil applications. During this period the basic research was conducted that laid the foundation for a series of flight research vehicles. The third phase was the period of flight research hardware, between 1970 and approximately 1976. The final phase, which continues through the present, has seen a resurgence of interest in VTOL for military applications while interest in pure STOL has virtually vanished.

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110 See I.M. Davidson, "The Jet Flap," Journal of the Royal Aeronautical Society, Vol. 60 #541, January 1956. It was elaborated by J.G. Lowry, et al., in *The Jet Augmented Flap*, Institute of Aeronautical Sciences Preprint #715, January 1957.

111 The externally blown flap was first reported by J.P. Campbell and J.L. Johnson, in *Wind Tunnel Investigation of an External-Flow Jet-Augmented Slotted Flap Suitable for Applications to Airplanes with Pod-Mounted Engines*, NACA TN-3898, September 14, 1956. What became known as upper-surface blowing was first reported by T.R. Turner, E.E. Davenport, and J.M. Riebe, *Low-Speed Investigation of Blowing From Nacelles Mounted Inboard and on the Upper Surface of an Aspect Ratio 7.0 35-degree Swept Wing with Fuselage and Various Tail Arrangements*, NASA Memorandum 5-1-59L, 1959.

Most of NASA's initial work in V/STOL was devoted to supporting a series of interservice prototypes.[112] In addition to their extensive work on the XC-142 tilt wing, the X-22 tilt-duct, and the XV-5 fan-in-wing, NASA pilots participated in a number of flight test evaluations on STOL aircraft developed and built by other organizations. These included: the German Stroukoff YC-134 (1961); the Lockheed NC-130B (1963); the Japanese UF-XS seaplane (1964);[113] the Boeing 367-80 fitted with boundary layer control (1964);[114] the French Breguet 941 prototype (1964);[115] and the Army Counterinsurgency (COIN) aircraft (1965).[116]

Interest in Civil STOL. By the mid-1960s a convergence of interest was under way between the FAA, NASA, and Congress to investigate short takeoff and landing as a means for improving the civil air transportation network (Congress was also concerned about potential loss of leadership to foreign countries in the STOL area). Preliminary studies concluded that STOL service was likely to be economically marginal, but urged a vigorous technology development program aimed at reducing operating costs.[117] An FAA-led interagency task force urged a greater government effort in 1965,[118] and NASA stepped up its own systems studies with various aircraft manufacturers.[119] The NASA and FAA enthusiasm was further reinforced by a 1968 report from the National Academy of Engineering, by various special hearings before Congress, and by the joint DoT/NASA/DoD Civil Aviation R&D (CARD) policy study conducted between 1969 and 1970.

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112 See TM-X-76292, *NASA Conference on V/STOL Aircraft, A Compilation of Papers Presented.* November 17-18, 1960.

113 See N.J. Vagianos, et al.; *Flight Test Evaluation of the UF-XS Japanese STOL Seaplane*, Naval Air Test Center FT 2121 031R 64, August 1964 (AD 625 722).

114 L.B. Gratzer and T.J. O'Donnell, *The Development of a BLC System for High Speed Airplanes*, AIAA Paper 64-589, August 1964.

115 H.C. Quigley, R.C. Innis, and C.A. Holzhauser, *A Flight Investigation of the Performance, Handling Qualities, and Operational Characteristics of a Deflected Slipstream STOL Transport Airplane Having Four Interconnected Propellers*, NASA TN-D-2231, 1964.

116 T.W. Feistel, C.A. Holzhauser, and R.C. Innis, *Results of a Brief Flight Investigation of a COIN-Type STOL Aircraft*, in NASA SP-116, 1966.

117 R.K. Waldo, et al., *An Economic Analysis of Commercial VTOL and STOL Transport Aircraft*, Stanford Research Institute, FAA-ADFS-25, February 1965. (AD 614 598)

118 Senate Document 90, p. 243. Members included Halaby, Alan S. Boyd (CAB), Willis M. Hawkins (Army), Robert W. Morse (Navy), Alexander H. Flax (Air Force), Calvin Muse (DoD), Raymond L. Bisplinghoff (NASA OART), and Clarence D. Martin (DoC).

119 Bernard L. Fry, "Review and Evaluation of Boeing Designs for the NASA Short-Haul Commercial Transport Study," in NASA SP-116. K.R. Marsh, J.J. Santamaria, and R.B. English, "Summary of LTV Feasibility Studies," in NASA SP-116. R. Scherrer, W.C.J. Garrard, E.M. Davis, and W.D. Morrison, "NASA-Lockheed Short-Haul Transport Study," in NASA SP-116.

Flight Research Hardware. A key event in the evolution of NASA's STOL program occurred in 1968 with the founding of the V/STOL Projects Office at the Ames Research Center. Their first project was the modification of a Navy OV-10 Bronco to include the Rotating Cylinder Flap concept, which essentially acted like a jet flap without the need for internal air ducting. This was followed in 1970 by the Augmentor Wing, a joint project with the Canadian government (see Figure 3-3).[120] The Augmentor Wing Jet STOL Research Aircraft (AWJSRA) was a C-8 Buffalo modified with turbojet engines and an augmentor jet flap.[121] The aircraft could produce usable lift coefficients of about 4.5 and take off in less than 1000 ft of runway, but unfortunately little attention was paid to noise during the design modifications and the aircraft made a terrible public impression.[122]

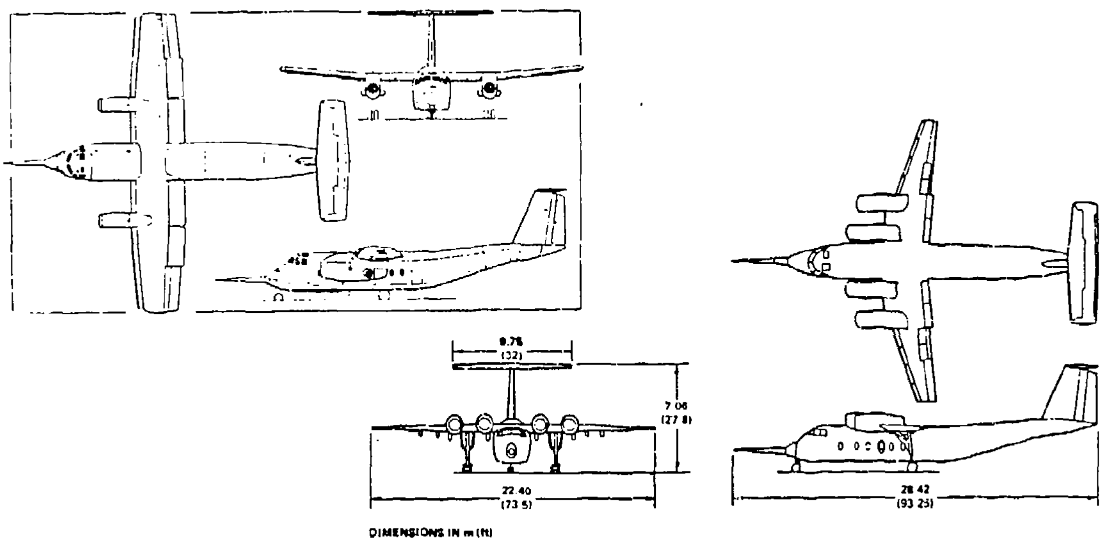

Figure 3-3. Major elements in NASA's powered-lift research program include (left) the Augmentor Wing Jet STOL Research aircraft, and (right) the Quiet STOL Research Aircraft (QSRA).
Source: *Jane's All the World's Aircraft*, various years.

QUESTOL. The 1971 CARD Study placed top priority on aircraft noise reduction and congestion relief. NASA proposed to combine both elements in a new program that would be both demonstrator and research vehicle for quiet STOL jetliners.[123] The program

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120 J.E. Middlebrooks, H.C. Ti. ney, and D.C. Whittley, *The Evolutionary Development and Current Status of the Augmentor Wing Concept*, SAE Paper No. 700812, October 1970.

121 R.H. Ashleman and H. Skavdahl, *The Development of an Augmentor Wing Jet STOL Research Airplane (Modified C-8A)*, NASA CR-114503, August 1972.

122 T.N. Aiken, "Advanced Augmentor Wing Research," in NASA SP-320, 1972.

123 Thomas L. Galloway, "Future Short-Field Aircraft," in NASA SP-320.

was dubbed QUESTOL, and in November 1972 Lockheed-Georgia was selected as the prime contractor. Since the two QUESTOL vehicles were expected to cost more than $100 million, NASA sought to structure the program as a cost-sharing venture with a private consortium. The aircraft manufacturers strongly resisted this approach, however, and the project was realigned as a more conventional government contract. Less than three months after the award to Lockheed, however, NASA cancelled the program. It was widely acknowledged at the time that the Office of Management and Budget viewed QUESTOL as extravagant, and unnecessary in light of the Air Force's decision to proceed with the Advanced Medium STOL Transport (AMST) program. To protect QUESTOL and stay within the budget ceiling provided by OMB, OART would have had to cancel all its other V/STOL projects plus reduce QUESTOL to a single vehicle on an extended schedule; given the availability of AMST aircraft this move could not be justified.

QCSEE. Even before its cancellation, it was clear that the engines for QUESTOL represented as much of an advance as anything on the airplane.[124] Originally QUESTOL was to have used new engines specially developed for the purpose, but plans soon slipped so that QUESTOL would have been flown first with existing engines and then retrofitted with advanced engines. When QUESTOL was cancelled the engine program was continued, expanded in scope to investigate engines for both upper surface and externally blown flaps, but reduced in cost by not making the engines flightworthy. The Quiet Clean STOL Experimental Engine Program (QCSEE) was formally initiated at Lewis in FY73; in January 1974 General Electric was selected to build two experimental engines based on the core of their F101 engine developed for the B-1 bomber.[125] One engine was specially designed for over-the-wing installation typical of upper-surface blowing, the second engine was designed for under-the-wing installation of an externally-blown flap configuration. Both engines tested a number of advanced concepts including very high bypass ratios (10 for the USB engine, 12 for the EBF), extensive use of composite construction materials, advanced acoustic suppression materials, a variable-pitch fan, reduction gearing to drive the fan, a variable-area fan nozzle, and digital electronic engine controls. The noise goals for the QCSEE engines were probably the most stringent ever set: 95 EPNdB at 500 feet, or about 82 EPNdB at normal FAR-36 measuring distances.

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124 R.J. Denington, R.W. Koenig, M.R. Vanco, and D.A. Sagerser; "STOL Propulsion Systems", in SP-320.

125 See Carl C. Ciepluch, "QCSEE Program," in NASA SP-381.

When NASA had begun its research into powered-lift STOL in the late 1960s, the military had no formal requirement for such an aircraft and was not a major participant in the research. This changed by 1970, when the Air Force Flight Dynamics Laboratory undertook a technology readiness program[126] to support the newly proposed Medium STOL Transport program, aimed at developing a replacement for the C-130.[127] FDL and NASA agreed that since NASA was pursuing the Augmentor Wing, the Air Force would focus on other concepts such as externally blown flaps. In 1972 the Aeronautical System Division's Prototype Programs Office issued an RFP for a new transport, now dubbed the Advanced Medium STOL Transport, or AMST. Boeing and McDonnell-Douglas were selected to build two copies each of their respective designs (see Figure 3-4). Boeing's entry, the YC-14, used two high-bypass ratio turbofans (CF6-50) in an upper-surface blowing configuration, while McDonnell-Douglas used four low bypass-ratio JT-8D-17s in an externally blown flap arrangement for its YC-15.

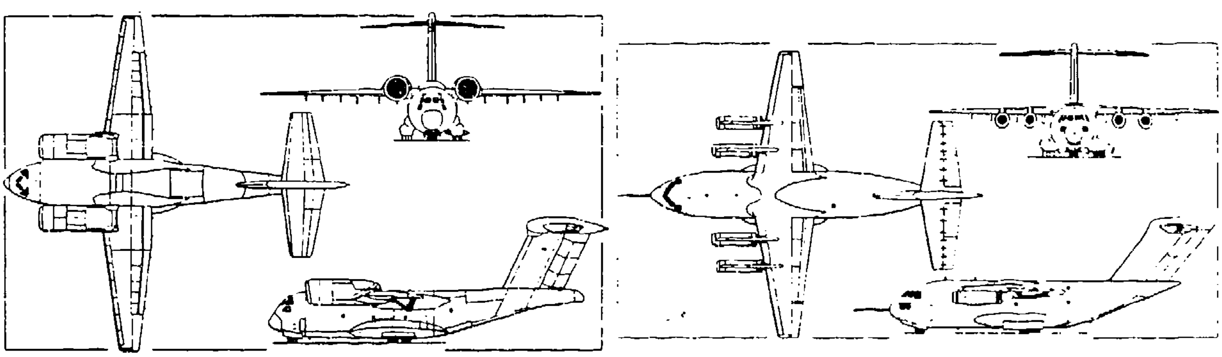

Figure 3-4. The Air Force Advanced Medium STOL Transport (AMST). Left, the Boeing YC-14 with upper-surface blowing. Right, McDonnell-Douglas YC-15 with externally blown flaps.
Source: *Jane's All the World's Aircraft*, various years.

The AMST aircraft were flying by 1976, and though NASA had little direct role in their development, they participated in a joint test program with the Air Force.[128] The AMST program was cancelled in 1978, with both entries apparently judged too expensive relative to the venerable C-130 (still in production at this writing).

[126] R.B. Lowry and G.S. Oates, Air Force STOL Tactical Transport Technology Program, SAE Paper #710758, September 1971.

[127] See AFFDL-TR-71-26 Vols. I & II, *STOL High-Lift Design Study*, by Fred May and Colin Wilson, The Boeing Company. April 1971.

[128] E.J. Montoya: "NASA Participation in the AMST Program", in NASA SP-406, 1976.

QSRA. Although the AMSTs provided important data on propulsive lift performance, stability, and control, they were built as prototypes, not as flexible research tools. Equally important, they were not built with noise reduction as a specific goal. When QUESTOL was cancelled, NASA began examining options for a less expensive flight research airplane that could investigate low-noise STOL operation. The concept emerged from Ames and was first presented to Congress in March of 1974 (FY75 Authorization Hearings) when NASA requested $8 million to proceed with the detailed design and fabrication for an aircraft to be known as the Quiet STOL Research Aircraft (QSRA). Like the Augmentor Wing, the QSRA was to be built around an existing airframe, the Buffalo, and would use existing engines built for the Air Force A-9 attack plane. QSRA was conceived as an extremely quiet vehicle with upper surface blowing. To save money the aircraft was restricted to a low-speed flight regime only, with landing gear and leading edge flaps fixed in a down position. Compared with QUESTOL, QSRA was to have lower cost, higher lift coefficients, and lower noise. Boeing and Lockheed conducted preliminary design studies during FY74, and in 1975 Boeing was selected as contractor. The aircraft was delivered to Ames in August 1978.

STOLAND. A key motivation behind the STOL effort was the utilization of the aircraft in areas already conjested with existing traffic.[129] In addition, the short runways meant that the absolute accuracy of the touchdown point was very important. Together these factors made navigation and guidance of critical importance. Working with the FAA, Ames took the lead in a series of research efforts to define how STOL aircraft should be best operated in the terminal environment, and what changes would be required in the existing ATC system.[130] A series of terminal-area flight experiments were conducted to develop data and requirements for future systems. For example, Ames pilots flew time-constrained, steep, decelerating approaches using three different navigation aids (MLS, VOR/DME, and TACAN) under a variety of traffic and weather conditions.[131] The results then served as the basis of further work for both on-board and ground-control systems. The emphasis centered around the development of so-called "4-D Guidance," which sought to have the aircraft at a specific point in space at a specific time.[132] The ATC system would

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129 In Paul Peterson, R.H. Sawyer, and M.D. McLaughlin, "Integration of STOL Airplanes into the ATC System," in NASA SP-320.

130 Much of this research was transferred or adapted from previous work begun for the SST.

131 D.W. Smith, D. Watson, and J.V. Christiansen, "Terminal-Area STOL Operating Systems Experiments Program," in NASA SP-320.

132 T. Peesvardi and H. Erzberger, "4-D Guidance of STOL Aircraft," in NASA SP-320.

specify the time and place, and an on-board control system would do the rest. The Ames program consisted of a series of increasingly sophisticated on-board systems, culminating in STOLAND system. STOLAND was a modular system including air data sensors, cockpit displays and a large on-board computer connected to servos driving the control surfaces. Developed by Sperry and validated in ground simulators, STOLAND was a sophisticated research tool that allowed a range of pilot options from fully manual to fully automatic landings.[133] Other research concentrated on airworthiness and certification[134] and passenger acceptance.[135]

Decline of Civil STOL. Even as QSRA was in development, however, NASA began to deemphasize powered lift technology. By the mid-1970s it was clear that earlier projections about traffic growth and congestion would not be fulfilled, and the continuing technology programs, though successful in meeting noise and performance goals, did not offer hopes for dramatic operating cost reductions (this is discussed further in Section 5.1). Systems studies conducted by Stanford University suggested that QCSEE engine technology could be combined with mechanical flaps to provide 4000 ft runway capability for 150-passenger transports, and that lengthening the runway at the few airports that could not accommodate such an aircraft would be more cost-effective than developing and operating an entire fleet of powered-lift transports.[136] No new STOL programs were initiated after the QSRA, although large-scale R&T effort continued through 1978. The AMST, never a top Air Force priority, was killed in 1978 primarily on the basis of cost. By 1976, powered-lift STOL was the last item mentioned in Congressional testimony and was no longer cited as a priority. In 1978 the R&T base funding for powered lift was drastically reduced. Most of the contracted and in-house work at Ames was terminated, along with work on aeroacoustics and loads at Langley.

The flight research programs already under way were continued. The last QCSEE engine was delivered to Lewis in July 1978; testing continued into mid-1979. AMST flights continued through 1979, but NASA elected not to continue an independent series

133 Q.M. Hansen, L.S. Young, W.E. Rouse, and S.S. Osder, *Development of STOLAND, A Versatile Navigation, Guidance, and Control System*, AIAA Paper 72-789, August 1972.

134 J.E. Cayot, R.A. Chubboy, and C.S. Hynes, "Program Plan to Develop Airworthiness Standards", in NASA SP-320.

135 See "Symposium on Ride Quality," NASA TM X-2620, 1972.

136 See Richard S. Shevell, *Studies in Short Haul Air Transportation in the California Corridor*. NASA CR-114634, July 1973 (N73-32842 & N73-32843), and *Further Studies in Short Haul Air Transportation in the California Corridor*. NASA CR 137485, July 1974.

when the Air Force completed its tests, and the four prototypes were placed in storage. The QSRA was delivered to Ames in 1978, and has conducted a successful flight test program that continues at the time of this writing. A particularly successful series of tests were conducted as a joint venture with the Navy, where the QSRA made a series of takeoffs and landings from an aircraft carrier. In recent years QSRA tests have continued but without fanfare: in fiscal years 82-84 the QSRA was the only reference to powered lift technology in NASA Congressional testimony. Within NASA there had been arguments for a follow-on to explore the high-speed flight regime, but these were effectively killed when the Reagan Administration recommended termination of all commercially-oriented R&D projects in the FY83 budget. FY84 projections showed the RTOP zeroed after FY82, but the aircraft has apparently been kept flying largely to forestall the impression that the Japanese have taken over leadership in the powered lift field.

As is typical in many NASA cases, the physical resources and personnel have not necessarily been dispersed, but have been shifted and reassigned. The decline of STOL has been paralleled by a great increase in VTOL and especially rotorcraft. The Navy effort to develop V/STOL absorbed a significant NASA effort until it wound down. More recently, there has been a large emphasis on short takeoff with vertical landing (STOVL) for military fighters.

Impact. As in the Aircraft Noise case, the most obvious conclusion about the NASA STOL research is that it has not led to the type of operational vehicles originally envisioned. In its FY72 budget submission, for example, NASA estimated an $8.8 billion market for powered-lift STOL in 1985; when that date passed not a single civil vehicle was even in development. The Augmentor Wing was retired to Canada in the late 1970s.[137] The QUESTOL was cancelled before it became a reality. The AMSTs were cancelled before entering production. The QSRA continues to fly, but the planned high-speed follow-on has never been pursued. The primary reason why STOL was not adopted appears to be that the traffic base and congestion failed to develop as predicted. Even if they had, however, it is unclear whether powered-lift transports would have had sufficiently attractive operating economics to justify their utilization in the face of rapid increases in fuel prices that occurred during the 1970s. Thus in this sense, the focused NASA effort to develop STOL technology has been disappointing. The issue is not,

[137] W.S. Hindson, G.H. Hardy, and R.C. Innis, *A Summary of Joint U.S.-Canadian Augmentor Wing Powered-Lift STOL Research Programs at the Ames Research Center, 1975-1980.* NASA TM 81215, July 1980 (N80-28373).

however, that there have been no benefits from the NASA program, but rather who has used the research and how long it has taken to pay off.

Most of the American returns from NASA's STOL program have been secondary benefits. Out of the STOL research program came a panoply of developments that have found application in conventional air transport systems, including microwave landing systems, advanced flight simulators, 4-D flight management techniques, and advanced air traffic control algorithms. The blown-flap technology has been incorporated in the C-17 transport now under development. The technology developed in the QCSEE program has found application in the advanced turboprop program and competing concepts. In particular, the International Aero Engines (IAE) 30,000-pound thrust SuperFan proposed for the A-330, A-340, and 7J7 aircraft[138] uses many of the concepts (very high bypass ratio [17-20], gearbox-driven, single-stage fan with variable-pitch blades) developed for and proven during the QCSEE program.

The most direct utilization of STOL technology has been in other countries. Canada, for example, is currently producing a 4-turboprop passenger transport, the DASH-7, and a twin-engine derivative, the DASH-8. The Soviet Union recently displayed its AN-74 transport, a production version of the AN 72 research aircraft. Japan continues development of its ASUKA research aircraft, a Kawasaki C-1 transport modified for upper surface blowing.[139] All of these developments have benefited heavily from NASA research; the extent to which this is good or controllable is discussed in Section 8.1.

There is strong evidence that powered-lift applications will yet emerge. Recent NASA studies note the value of powered lift as a means of increasing payload rather than reducing runway requirements.[140] Many of the same factors that motivated the civil STOL effort in the late 1960s appear to be re-emerging in the 1980s. The hub-and-spoke networks emerging under deregulation are very similar to those originally envisioned for STOL, and the increase in traffic is again straining system capacity. Presently most feeder routes use small commuter airliners, of which there are already a large number of designs.

[138] IAE is a five-nation consortium made up of Pratt & Whitney, Rolls-Royce (U.K.), Japanese Aero Engine Company, MTU (Germany), and Fiat Aviazione (Italy), formed to develop the V.2500, a 23,000-lb thrust high-bypass ratio turbofan engine for the A-320. See "A-340 will be SuperFan powered," *Flight International*, 3/10 January 1987.

[139] To date, the Japanese have reportedly invested over $246M (Y36,000 million) in ASUKA, more than the entire NASA program. See *Jane's All the Worlds Aircraft*, 1984-85.

[140] Wallace H. Deckert and James A. Franklin, "Powered Lift on the Threshold," *Aerospace America*, November 1985.

This is the most vigorously growing segment of the airline market; if larger designs are eventually required, they will almost certainly need some type of powered-lift capability. Boeing has recently acquired DeHavilland of Canada, uniting the two companies with the most experience with powered-lift. A dedicated STOL Port is being built on abandoned docks near London. The Japanese continue to explore applications. In the military area, the Air Force "Project Forecast 2" identified an intra-theater STOL transport as one of the most promising systems for future development.[141]

3.3 HYPERSONIC FLIGHT TECHNOLOGY

At about five times the speed of sound, shock waves generated by the forward structure of an aircraft or missile angle backwards so sharply that they begin to impinge on other surfaces, and the stagnation temperatures are so high that air begins to dissociate into its component atoms. The resulting changes in aerodynamics, structures, and propulsion are so significant that this regime requires a separate body of theory and engineering practice.

The realm of hypersonic flight (roughly, flight speeds are between 5 and 25 times the speed of sound) is important for three general types of vehicles. The first is reentry bodies, which, upon entering the earth's atmosphere from space, will travel first at hypersonic speeds until aerodynamic resistance slows them. The second class of vehicles may be termed advanced space launchers, which would exit the atmosphere and place payloads in space, but in the process capitalize on atmospheric oxygen to reduce their onboard propellant load. The third class of vehicles would be cruise aircraft (hypersonic transports, or HSTs), which would seek hypersonic regime because the high speed offers presumed benefits in terms of military utility or economics. Only reentry bodies exist today, the other applications remain speculative. NASA has taken an active interest in all three, however, and over the years has probably invested over a quarter-billion dollars into hypersonic R&D (see Table 3-5).[142]

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141 "Forecast II: Art of the Possible," *Flight International*, 11 October 1986.

142 The data in Table 3-5 lists $85 million in current-dollar spending for hypersonic R&D. The 864 man-years charged to R&PM roughly doubles this, and since only about half the actual data is represented, it seems fair to double this amount again for a total estimate. This implies total NASA spending to date on hypersonics of about $350 million.

Table 3-5. Identifiable NASA Spending on Hypersonics (millions of current dollars)

Title	FY 61	FY 62	FY 63	FY 64	FY 65	FY 66	FY 67	FY 68	FY 69	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80	FY 81	Total
R&T Base	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.7	1.8	3.3	2.1	2.7	3.0	3.1	2.6	21.3
X-15	1.0	5.7	5.6	0.8	1.4	0.9	0.8	3.5														19.7
HRE					2.3	1.1	6.3	7.0	9.6	6.0	6.1	6.1	6.1									50.6
Total R&D($M)	1.0	5.7	5.6	0.8	3.7	2.0	7.1	10.5	9.6	6.0	6.1	6.1	6.1	2.7	1.8	3.3	2.1	2.7	3.0	3.1	2.6	91.6
Man-years			n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	140	144	171	91	87	84	82	65	864.0

UPN	Title		1974 m/y	1974 R&T$	1975 m/y	1975 R&T$	1976 m/y	1976 R&T$	TQ m/y	TQ R&T$	FY77 m/y	FY77 R&T$	FY78 m/y	FY78 R&T$	FY79 m/y	FY79 R&T$	FY80 m/y	FY80 R&T$	FY81 m/y	FY81 R&T$	FY82 m/y	FY82 R&T$
505-02-12	HS Vehicle Structures Technology	FRC	2	86	8	40	6	84	?	35			*									
505-02-12	HS Vehicle Structures Technology	LaRC	17	535	* 23	375	21	355	6 7	190												
505-02-14	HS Aircraft Structures	FRC									6	30	*									
505-02-54	HS Aircraft Structures Technology	FRC											4.6	0	* 0	0						
505-05-41	HS Propulsion Technology	ARC	4.6	155	6.9	157					na	na	0	?	0	0						
505-05-41	HS Propulsion Technology	LaRC	54	530	* 53	550	52	560	12	237	49	1147	* 0	0 -	0	0	not funded					
505-05-43	HS Propulsion Technology	LaRC	0	0	0	0	0	0			na	na	52	1719	* 0	0	505-32-93					
505-32-93	Hypersonic Propulsion Research	LaRC	0	0	0	0	0	0					0	0	47.6	1800	*44.6	1826	48	1997		
505-05-42	HS Research Engine	LaRC	6	0	0	0	0	0			na	na	0	0	0	0						
505-11-31	HS Aircraft Aerodynamic Technology	LaRC	44	1152	* 41	525	37	500	9.2	241	0	0	0	0	0	0						
505-11-33	HS Aerodynamics & Flight Testing	LaRC	0	0	0	0	0	0			35.8	947	30.1	996	* 0	0	d 505-31-73					
505-31-[illegible]	HS Aircraft Aerodynamics & Flight D	LaRC	0	0	0	0	0	0					0	0	36.8	1150	*37.1	1235	16.9	660		
505-32-73	Fundamental HS Propulsion Research		0	0	0	·0	0	0					0	0	0	0	0	0				
505-43-63	Hypersonic Airbreathing Vehicle Technology																					
505-43-83	High Speed Technology																					
506-26-10	Advanced Earth Orbital Thermo	LaRC	13	240	13	110	35	450	4	264												
516-56-01	HS Aircraft Systems Technology		0	0	0	0	20	1340	* 5	40	FY76		0	0	0	0						
516-56-02	HS Technology		0	0	0	0	0	0	0.5	55			0	0	0	0						
517-52-00	Hypersonic Research Technology		0	0	0	0	0	0					0	0	0	0						
521-71-01	Atmospheric Flight Experiment				* 40	150																
			140.	2698	*144	1757	*171	3289	*35.	1062	*90.8	2124	*86.7	2715	*84.4	2958	*81.7	3061	*64.9	265[illegible]		

Reentry Vehicles. The first research in hypersonic aerodynamics was done in Germany during the 1930s. Busemann explored the aerodynamic theory, while Sanger proposed the first application, a long-range rocket-powered boost-glider. Most practical research focused on supersonic aerodynamics, however, and it was not until the ballistic missile appeared to be a viable proposition in the early 1950s that the hypersonic regime began to receive widespread attention. Although most of the ballistic missile development took place under the direction of the military services, NACA devoted an increasing effort to the area of hypersonic aerodynamics and especially, aerodynamic heating. In 1951, for example, H. Julian Allen of NACA-Ames developed the blunt-nose principle. He concluded that the amount of kinetic energy which appears in the body in the form of heat is proportional to the ratio of friction force to total drag force acting on the body. Thus, the use of blunt bodies with high base drags proved to be an effective method for reducing the heat load.[143] This configuration was used on early reentry vehicles, both manned and unmanned. At Langley, research groups in Hypersonics and Gas Dynamics had been established in the late 1940s to pursue aerodynamics and heating problems of very high-speed flight.[144]

Ramjets. At high speeds the compressor used on turbojet engines becomes impractical and unnecessary; ram air alone provides sufficient compression for operation of an engine. The resulting "ramjet" is conceptually the simplest aircraft engine. The first ramjets were developed during the 1950s for supersonic missiles such as the Navaho and Bomarc. These engines used hydrocarbon fuels and subsonic burning; that is, the air inside the engine was decelerated below the speed of sound before reaching the combustion chamber. Lack of suitable high-temperature materials and the energy loss due to dissociation of the airflow were believed during the 1950s to limit ramjets to speeds of less than about Mach 4.[145]

The X-15. In June of 1952, the NACA Committee on Aerodynamics passed a resolution which recommended that NACA increase its program for the speed range between Mach 4 and Mach 10. This led by 1954 to a proposal for a manned, Mach 7 research airplane. A December, 1954 Memorandum of Understanding between the

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143 Edwin P. Hartman, *Adventures in Research*, NASA SP-4302, 1970, p. 216.

144 John V. Becker, *The Development of Winged Reentry Vehicles, 1952-1963*. Unpublished monograph dated May 23, 1983, p. 2.

145 John V. Becker, *A Hindsight Study of the NASA Hypersonic Research Engine Project*, unpublished NASA manuscript, July 1976, p. 2.

Air Force, Navy, and NACA established the X-15 program. Construction started in September 1957 and the first flight was made in June 1959. By the time the program was completed in 1968, the three X-15s had made 199 flights, reaching speeds as high as Mach 6.6 and altitudes of more than 67 miles.[146]

The X-15 was built with a "hot structure" concept that used a nickel-chrome alloy called Inconel X and titanium. Since airbreathing engines were believed impractical at the time the X-15 was initiated, propulsion was supplied by a 57,000-lb thrust rocket engine burning anhydrous ammonia (NH_3) and liquid oxygen (LO_2). NH_3 was selected over hydrogen apparently because of pilot safety considerations.

The X-15 proved to be a spectacular and successful program. Among the research areas advanced by the X-15 were hypersonic aerodynamics (where wind tunnel predictions were largely verified), aerothermodynamics (where heat flow through the turbulent boundary layer was 30-40 percent below predictions), simulators (where flight simulators were used for the first time on a manned aircraft) and control (where an electronic flight control system was developed as a stability augmentation system).[147]

X-20. During the 1950s there were three competing approaches for returning a man from space: ballistic, winged, or lifting body. Although the ballistic vehicle was adopted as the standard for all the early manned flights (Mercury, Gemini, Apollo) all three concepts were pursued at the research stage. Even as NACA was preparing flight experiments for the X-15, researchers at Langley and Ames were exploring the relative merits of high versus low lift-to-drag ratio boost-gliders for whatever would succeed the X-15.[148] NACA technology formed the basis of the Air Force HYWARDS study of 1956-57, and then the X-20 Dyna-Soar (for "Dynamic Soaring"), a piloted, delta-winged space glider to be launched atop a Titan III booster. Much of the work had been initiated at Langley in the early 1950s, and then transferred to the Air Force. In 1957 the Air Force decided to go ahead with a research vehicle, and in November 1959 Boeing was selected as the contractor.

The X-20 was a small vehicle, capable of carrying one man plus 1000 pounds of payload (mostly test instrumentation) and capable of only a few orbits. Its primary

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146 Richard P. Hallion, *The Path to the Space Shuttle: The Evolution of Lifting Reentry Technology*, Air Force Flight Test Center History Office, November 1983, pp. 16-17.

147 Wendell H. Stillwell, *X-15 Research Results*, NASA SP-60, 1965.

148 See *The Development of Winged Reentry Vehicles, 1952-1963*, for a discussion of this research.

structure was built of Rene 41, a nickel-based alloy, with a graphite-zirconia heat cap and molybdenum leading edges. The structure was "hot" in the sense that it absorbed heat and then radiated it away, with insulation protecting the internal components. The X-20 itself was to be engineless.

Originally, the Dyna-Soar was to be a research vehicle, exploring "the characteristics and problems of flight in the boost-glide test regime up to and including orbital flight."[149] The Soviet success with Sputnik placed an extremely high priority on manned orbital flight. Many in the Air Force expected NASA's Project Mercury to fail, and wanted Dyna-Soar available as a rapid substitute.[150] Even with Mercury's success interest in military missions in space grew even further, and Dyna-Soar came to be seen as a prototype for an operational vehicle. In 1961 the Dyna-Soar program was redirected without NASA consultation to eliminate most of its research aspects.[151] Most of the proposed missions , however, proved to be either unjustified or more easily accomplished by ballistic-reentry vehicles. Secretary of Defense Robert McNamara concluded that the X-20's research objectives could be met by firing small delta-wing subscale models on ballistic missiles, and the X-20 was cancelled in 1964 before construction of the first vehicle was completed. At the time the program was cancelled, some $410 million (about $1.2 billion in FY82 dollars) had been expended, with 2.5 years and $373 million estimated still to go before the first flight.[152]

Scramjets. Although the X-15 and the X-20 were important hypersonic test vehicles, neither had any provision for prolonged atmospheric flight. One of the key advantages of air-breathing engines is that they must carry only fuel, as opposed to a rocket which must carry both fuel and oxidizer. Prior to 1957 the only means of propulsion seriously considered for hypersonic flight was the large rocket engine. Work at NACA-Lewis in the early 1950s on external burning showed that supersonic combustion was possible; later work established the feasibility of using liquid hydrogen as an aircraft and rocket fuel. The first definitive assessment of supersonic combustion ramjets ("scramjets") was published by Weber at NACA-Lewis in 1958.[153] Although NASA interest

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149 *The Development of Winged Reentry Vehicles, 1952-1963*, page 35.

150 *Ibid.*, p. 41.

151 *Ibid.*, p. 48.

152 Hallion, *The Path to the Space Shuttle*, p. 25.

153 R.J. Weber and J.S. MacKay, *An Analysis of Ramjet Engines Using Supersonic Combustion*, NACA Technical Note 4386, September, 1958.

subsequently waned (Lewis was in the process of withdrawing from all airbreathing propulsion work), the scramjet concept became the subject of extensive research funded by the Air Force Aeronautical Propulsion Lab and Office of Scientific Research. This led to a series of proposals for an "aerospaceplane," an air-breathing space launcher that would take off horizontally, fly into orbit, and return to base like a conventional aircraft.[154]

The first major public discussion of scramjets came in April 1960, at an AGARD colloquium in Milan, Italy. There, A. Ferri of Brooklyn Polytechnic Institute established himself as what John Becker described as "the chief prophet of scramjet propulsion."[155] Ferri was but one of a small group of determined advocates who continue to press publicly for advanced demonstrations of scramjet applications.

Growing interest by the summer of 1962 led to a joint Air Force/NASA team to study hypersonic propulsion R&D. In 1964, the Air Force "Project Forecast" identified scramjets as an area meriting national attention. General Bernard Schriever, head of the Air Force Systems Command, established a special Task Force on scramjets and actively promoted development of a high priority national program. Although Schriever's proposed $50 million study was not funded, it did help prompt NASA to return to the hypersonic propulsion field.[156]

It was in this environment that NASA began to examine the need for a hypersonic research aircraft. In June of 1962, Albert J. Evans, then Chief of Propulsion and Vehicle Projects at NASA, announced to the Congress that NASA saw the need for a hypersonic cruise aircraft to follow the X-15. With a gross weight of about 100,000 pounds (approximately three times that of the X-15) the Hypersonic Cruise Research Aircraft would take off and land like a conventional aircraft, but would be capable of cruising at speeds up to Mach 10. Although the vehicle would require advances in aerodynamics and structures, the most intricate part was the powerplant. Described as a turbo-ram rocket concept, the engine was intended to (a) operate as a turbojet at speeds to Mach 3; (b) operate as a ramjet to Mach 8 or 10; and (c) operate as a hydrogen-oxygen rocket to propel

154 Hallion, *The Path to the Space Shuttle*, pp. 25-28. Hallion describes the overblown expectations placed on the Aerospaceplane, and the growing disenchantment of the Air Force Science Advisory Board with the whole program. The SAB concluded: "The so-called Aerospaceplane program has had such an erratic history, has involved so many clearly infeasible factors, and has been subjected to so much ridicule that from now on this name should be dropped. It is also recommended that the Air Force increase the vigilance that no new program achieves such a difficult position."

155 Becker, *Hindsight Study of HRE*, p. 5.

156 *Ibid.*, p. 23.

the vehicle into orbit (although orbital capability was not proposed for the HCRA). Of all the challenges associated with a hypersonic aircraft, the propulsion system was probably the greatest. When it became clear that the HCRA was overly ambitious, NASA developed a project to build an experimental scramjet and flight test it on an X-15.

The Hypersonic Research Engine. When one of the X-15s was damaged in November 1962 its manufacturer, North American Aviation, proposed to modify it during the rebuild to extend its capability up to Mach 8 and allow the aircraft to be used as a platform for testing experimental scramjet engines. These modifications were approved and funded by the Air Force. With the prospect of a carrier vehicle, NASA undertook to develop a research engine. As originally proposed in 1964, the Hypersonic Research Engine (HRE) project was to have three Phases: a feasibility study, construction and testing of a laboratory model, and construction of a flightworthy engine with testing on an X-15. An unusual and revealing hindsight study concerning the HRE has been prepared by Becker,[157] who describes how the 4-year $30 million program to produce a flight engine became an 11-year, $50 million effort that produced two ground-test models. The major realignment in the HRE program came in 1968, after the Air Force decided to withdraw from the X-15 program, and NASA subsequently cancelled further flights. In place of the Phase III flight program, NASA substituted a Phase IIA program that included a "Structures Assembly Model" (SAM) developed at Langley and tested in the 8-foot high-temperature structures tunnel, and the "Aerothermodynamic Integration Model" (AIM) developed at Lewis and tested in their Plumbrook hypersonic test facility. The SAM was regeneratively cooled with liquid hydrogen and was tested at speeds of up to Mach 7, thus becoming the first validated regeneratively cooled scramjet structure. The AIM, on the other hand, was used to study internal flows; although it was not a flight-weight structural design, it was used to study internal flows including combustion. The focus of the AIM on internal performance led to a net thrust (thrust minus drag) of approximately zero, which led to a skeptical reception on the part of many who reviewed the program.

START. When the X-20 was terminated the Air Force continued its lifting research through the Spacecraft Technology and Advanced Reentry Test (START) program. This consisted primarily of two smaller, unmanned vehicle programs, ASSET, and PRIME. ASSET was a series of six gliders that resembled the X-20, launched between 1963 and 1965 on ballistic missiles from the Eastern Test Range. PRIME was a

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157 *Ibid.*

series of four heavily-instrumented reentry bodies, also designated as the X-23A.[158] During tests in 1966 and 1967, these vehicles provided data that are today still among the most complete flight data available at hypersonic speeds.

The Space Shuttle. Although enthusiasts saw potential applications for hypersonic cruise aircraft, the key application driving scramjet technology was its use as propulsion for an advanced space launching system. Thus, when a vertical-launch, all-rocket system was selected for the Space Shuttle, much of the motivation for continued scramjet development was removed. If the Shuttle proved to be a setback for hypersonic propulsion, however, it was a boon to aerodynamics. During its development some 35,000 hours of wind tunnel time were spent, with much of the testing in the hypersonic regime.[159] Further, the Shuttle has provided an opportunity to correlate predictions with actual flight data. As the first winged vehicle to transverse the full flight regime, from Mach 25 to .1, the Shuttle has provided the opportunity to gather data in the free molecular, rarefied gas, and continuum flow regimes.[160]

The X-24C. By the early 1970s it was clear that the podded engine concept used on the HRE had severe problems (among them high external drag, high internal friction and coolant requirements, major shock and viscous interactions in the combustor)[161] and was not likely ever to form the basis of a practical vehicle. Researchers at Langley, meanwhile, had been exploring the concept of "modular" propulsion units. The idea was to use a rectangular (2-dimensional) inlet to fully capture the hypersonic boundary layer. Similarly, a rectangular nozzle would be used and the nozzle expansion could be integrated with the aircraft afterbody. The modular concept had the advantage that individual segments could be tested in the lab, with a number of modules operating in parallel to power an actual aircraft.

The primary disadvantage of the concept was that since it relied on external compression (before the inlet) and expansion (behind the nozzle) the actual design of the propulsion module could not be separated from that of the aircraft it would power. To test the modules in flight, a new research aircraft would be needed.

158 Hallion, *The Path to the Space Shuttle*, p. 31.

159 J.L. Stollery, "What has Hypersonics Research led to?," *Aerospace*, September 1982.

160 See NASA CP-2283, *Shuttle Performance: Lessons Learned*, October 1983.

161 Becker, *Hindsight Study of HRE*, p. 30.

In May of 1974 NASA-Langley and the Air Force Flight Dynamics Laboratory set up an ad hoc study group to examine the concept of a common research program in hypersonics. The result was the X-24C, a manned, air-launched lifting body based loosely on the X-24B lifting body used for low-speed approach and landing experiments. The X-24C was to be powered by the same XLR-99 engine used on the X-15, but with a designed-in capability to test modular scramjets integrated into the underbody. Designed for 40 seconds of cruising time at Mach 6 and a peak speed of Mach 7.4, the vehicle would use an insulation thermal protection system but would include provisions for testing actively-cooled structures. Proposed in FY76, the X-24C received no substantial funding support and was terminated in FY77.

Recent Research Activity. With the demise of the X-24C, interest in hypersonic research lagged again. NASA continued a three-pronged effort in its R&T base at Langley (covering aerodynamics, propulsion, and structures, see Table 3-5), but even this effort was drastically scaled back in 1981. Efforts to upgrade the 8-foot High-Temperature Tunnel began in 1983, with the goal of adding an oxygen-enrichment system to allow the methane-air combustion-heated test system to simulate air for propulsion testing.

The first Space Shuttle flew in 1981, providing a new source of hypersonic flight data. Moreover, with the phasedown in Shuttle development interest began to turn to its next-generation replacement. British Aerospace proposed Hotol, an unmanned horizontal-takeoff single-stage-to-orbit system propelled by an undisclosed airbreathing/rocket propulsion system. The Air Force began studying the Trans-Atmospheric Vehicle, a rocket-powered single-stage-to-orbit concept for on-demand launches of small payloads. A multi-year NASA effort to compare concepts for a next-generation launch vehicle concluded that vertical take-off concepts offered much lower weight and cost than horizontal-takeoff counterparts, and that the dry weight of air-breathing boosters consistently exceeded "by an order of magnitude" the dry weight of rocket boosters.[162] Meanwhile, however, a DARPA effort named "Copper Canyon" was studying the technology for scramjets and reaching the opposite conclusion. The Air Force "Project Forecast II" again identified scramjet-powered space launchers as an important national priority, and on February 4, 1986, President Reagan announced a program to develop what

162 See James A. Martin, "Orbit on demand: In this Century if Pushed," *Aerospace America*, February 1985.

he termed an "Orient Express," a scramjet-powered aircraft that could cruise hypersonically in the atmosphere or carry payloads into orbit. At the time of this writing it is too early to tell whether the National Aerospace Plane (NASP) effort is (like the Stealth aircraft) built around some highly classified technical breakthrough not anticipated in earlier studies, or whether (like the Strategic Defense Initiative) it is a research program being sold on the promise of applications based on future developments. NASP has, however, led to the almost frantic revitalization of the nation's hypersonic research program. In FY87 NASA budgeted $45 million for "Transatmospheric Research and Technology," and proposed $65M in FY88. This is approximately twenty times the spending rate of five years before, and roughly comparable (in real terms) to the previous peak of 1968, when the agency was flying the X-15 and developing the HRE.[163]

Impact. In contrast to the Aircraft Noise and Powered-Lift case studies, hypersonics has had a much smaller impact on civil applications. Thus it appears to follow the traditional pattern of a NACA program, advancing technology whose exact application is quite vague but probably military in nature, with the expectation that the military services will take over development once a promising match between technology and opportunity can be made.

So far, it has proved very difficult to fund flight research vehicles to close the gap between laboratory or sub-scale tests and prototypes of operational systems. The rigorous demands of hypersonic flight lead to complex technology and attendant high costs. The interest of potential clients for this technology has been cyclical: the Air Force periodically pushes for an operational system, but when it becomes clear that an economically and technically attractive system is still far away, the interest fades. In NASA, interest is connected to the perceived need for a next-generation space launcher. Each time a new generation of space launchers is proposed, the airbreathing versus rocket trade-off is reviewed, providing a stimulus for continued hypersonic research. To date, the trade-off has always favored rocket booster systems. This trade-off is currently being examined again as the nation begins to seek a successor to the Space Shuttle.

Throughout these cycles, OAST has clearly been the nation's primary repository for hypersonic competence. This has not been due necessarily to conscious planning on the

[163] The contrast between NASP and any previous NASA program is striking. In 1976, for example, Lockheed proposed that it would cost $50-$65 million to modify the X-24 into the X-24C, without flight tests or engines (see H.G. Combs, *Configuration Development Study of the X-24C*, NASA CR-145032, p. 270). Today, DARPA is projecting a budget of over $3 billion for the X-30 NASP.

part of headquarters; frequently, it is the persistence of individual researchers in the field centers who sustain research even when it is out of favor.

Hypersonics also illustrates another characteristic typical of much aeronautical research: it is heavily dependent on outside developments. The National Aerospace Plane, for example, is heavily driven by developments in materials and computational capability. It is the synergy between many different technologies that make a system possible or not, and it is precisely this synergy that requires a multidisciplinary institution to harness.

Note: Since the time this case study was prepared in 1985/6, the continued resurgence of interest in hypersonic flight through the National Aerospace Plane program has resulted in a flood of literature, both historical and technical, on hypersonics. Prime among these is *The Hypersonic Revolution*, a series of eight studies of hypersonic programs. Edited by Richard P. Hallion and available through the Special Staff Office of the Aeronautical Systems Division at Wright-Patterson AFB, Ohio, the study is more comprehensive than the summary presented in this report.

It should also be noted that neither the case study presented here nor Hallion's work fully reflect the continuing work of the Office of Naval Research and the Applied Physics Laboratory at Johns Hopkins University in hypersonics. Much of that work has been oriented around missiles for air defense and hence the use of storable fuels, but the contributions have been broad.

CHAPTER 4. AERONAUTICAL R&D AND THE FREE MARKET

Why should the government fund aeronautical R&D at all? The fact that the government purchases airplanes is not in itself a justification for the government to fund a separate and wide-ranging R&D program; the government, after all, purchases many other products without the need for dedicated R&D programs. This chapter examines the question of how markets affect incentives for R&D, and examines to what degree the assumptions of a free market hold true in aeronautics.

The three conclusions that emerge are not surprising, but are important prerequisites for the chapters that follow. The first conclusion is a very general one--that under certain circumstances, private companies may tend to underinvest in R&D relative to what society as a whole would rationally invest if the full costs and benefits could be known and compared. The second conclusion is that many of these circumstances exist in aeronautics, along with other conditions that make many traditional free-market analogies invalid. The third conclusion is that, in broad terms, this private sector underinvestment does indeed exist in aeronautics, even though the private sector spends a considerably higher fraction of its own resources on R&D than is the case in other comparable industries. Together, these suggest that the basic choices are for the government to supplement private funding in aeronautical R&D or to accept the societal consequences of underinvestment. These conclusions leave open the issue of how much the government should invest and in what directions; these questions will be examined in subsequent chapters.

4.1 R&D IN AN IDEAL MARKET

Technical progress is one of the most important engines that drive economic growth.[164] Thus, it seems surprising to conclude that private companies inherently tend to underinvest in research and development. Yet those who have studied the economics of

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164 See, for example, Edwin Mansfield, *The Economics of Technological Change* (W.W. Norton & Co., New York, 1968); or Kenneth J. Arrow, *The Rate and Direction of Inventive Activity* (Princeton University Press, 1962), or R.R. Nelson and S.G. Winter, "In Search of a Useful Theory of Innovation," *Research Policy* 6, 1977.

R&D have repeatedly reached just such a conclusion. A 1967 Brookings Institution study stated: "The fact that much of the knowledge created through basic research and experimental development goes into the public domain means that private decisionmaking, guided by the profit incentive, will fail to seize many opportunities which have a high rate of return for the economy as a whole."[165] These arguments center around five basic concepts:

Appropriability. A key assumption in any investment is that the investor will be able to capture (secure for himself) the returns of an investment. In R&D, this is frequently not the case. In many areas, the important information is that something can be done; once this has been established the accomplishment can be duplicated rapidly. Thus, the originator expends the high costs, but cannot exclude others from benefiting from the resulting development.[166]

Probability of payoff. As noted in Chapter 1, even though the payoffs from a successful development may be very high, the probability of an individual research project or idea becoming successful is low. This is partly because the payoff generally depends not just on the technical success of the research, but also on its utilization, where many additional factors (economic, social, political, market timing, etc.) have influence.

Long time scale. The length of time required for an investment in research to be translated into a practical application is often very long. The average development time for a modern transport aircraft is about five years, and typically seven years for engine development. The time between initiation of a research idea and its use in a development project is much longer: research on graphite-epoxy composites, for example, began in the early 1960s. The first graphite parts were used in secondary structures on production aircraft in the early 1980s; they have yet to be used in primary structures of large production aircraft (although a few military (AV-8B) or general aviation (Beech Starship) are in development using graphite primary structures).

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165 Richard R. Nelson, Merton J. Peck, and Edward D. Kalachek, *Technology, Economic Growth, and Public Policy* (Brookings Institution, 1967) pp. 87-88.

166 The patent system was created to address this problem, but the patent system has never proved very applicable in aeronautics. One of NACA's first tasks was to establish a system to share patents among the various aircraft manufacturers in order to resolve legal disputes between the Wright-Martin and Curtiss-Burgess companies that threatened to shut down American aircraft manufacture during World War I. See Alex Roland, *Model Research*, pp. 37-43. The resulting agreement "established that the American aviation industry would operate without major patents."

Even assuming that the eventual benefits of a research project are known, when market interest rates are applied, the discounted net present value of the research can be very small. Further, the incentive structures in private firms are often such as to reward short-term performance rather than long-term investment, implicitly raising the discount rate beyond actual market values.

Divisibility. In some instances, return is commensurate with investment. In many areas of R&D, however, a threshold exists below which partial investment is not practical. This is particularly true in the case of facilities, which may be essential to the conduct of research but so expensive as to be impractical for a single firm to justify.

Another important aspect of divisibility is the fact that significant advances are frequently the result not of a single, revolutionary development but of a series of gradual, evolutionary improvements that interact together in a system. To develop any one piece of the system is of little value, since the value is provided by the synergy of many advances working together. This is frequently described as the need for a "critical mass" in research level.

Externalities. Investment analyses reduce all considerations to a common currency, usually financial. Thus, factors that do not appear explicitly in such calculations are known as externalities, and they frequently impact R&D. One of the most important externalities is the existence of public benefits or disbenefits. In the absence of regulation, for example, the impact of aircraft noise is not included in a direct cost to airlines, and thus they have few incentives to purchase aircraft that are in any way compromised in order to produce lower noise. Manufacturers, in turn, have little incentive to develop or produce such aircraft. Externalities frequently lead to under- or overproduction of goods relative to the amount that would be produced if externalities were accounted for.

Together, these considerations make it difficult (and sometimes impossible) to justify R&D on the basis of its net present value.[167] A corollary argument is that in cases where "public goods" are at stake the government may wish to compensate for private

167 A rare illustration of how short-term economic pressures discourage R&D was recently provided by Hughes Aircraft after it was purchased by General Motors. Prior to its acquisition by General Motors in 1983, Hughes had one of the highest rates of R&D expenditure in the industry. This resulted in a reputation for highly innovative work, but much of it was made possible by the fact that Hughes' parent, Hughes Medical Foundation, was non-profit. Shortly after its acquisition by GM, R&D spending at Hughes began to decline. This, of course, is not confirmation of underinvestment (perhaps Hughes was spending too much on R&D to begin with) but it does support the element of the theory that a free market will tend to force R&D downward.

underinvestment by funding R&D itself. As noted in Section 1.1, the argument is frequently made that government investment is most appropriate in basic research, where the payback times are longest, the results are most uncertain, and the applications least obvious. As R&D progresses towards development, these factors change and government involvement become less appropriate. As noted in Chapter 1, many observers conclude that the government is a poor judge of market conditions, and should stay away from market-dominated development decisions.[168]

4.2 AERONAUTICS AS A FREE MARKET

A $44 billion industry in 1985, aeronautics is made of four major markets: U.S. commercial sales, foreign commercial sales, U.S. military sales, and foreign military sales.[169] The relative size of these markets in recent years is shown in Figure 4-1.

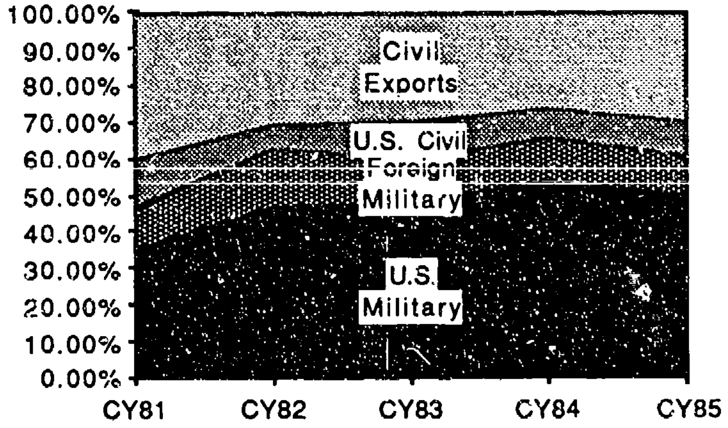

Figure 4-1. Breakdown of the aeronautics market for 1981-85. The data is shown as percentage of sales for aircraft, engines, and parts. In 1985 the total sales exceeded $44 billion, with civil exports accounting for $12.9 billion, domestic civil sales $4.1B, foreign military sales $4.9B, and domestic military sales about $21.8B.
Source: Aerospace Industries Association, *Aerospace Facts and Figures 1986-1987*, pp. 28 and 137. The AIA data are adapted from Bureau of the Census reports.

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[168] The SST is usually the aeronautical example cited in support of this argument. See George Eads and Richard R. Nelson, "Governmental Support of Advanced Civilian Technology: Power Reactors and the Supersonic Transport," *Public Policy*, 19 (1971) pp. 403-427.

[169] "Aeronautics" is used here to include the Standard Industrial Classifications (SIC) for Aircraft (#3721), Aircraft Engines and Engines and Parts (SIC #3724), and Aircraft Parts and Auxiliary Equipment (SIC #3728).

In his 1980 study *The Defense Industry*, Jacques Gansler wrote "In order to understand the economic operation of the U.S. defense industry, it is first absolutely essential to recognize that there is no free market at work in this area and that there likely cannot be one because of the dominant role of the federal government."[170] Gansler listed thirty assumptions of a free market and explained why each was invalid in the defense industry. These characteristics are listed in Table 4-1.

In 1985 the U.S. military market accounted for about 50 percent of all aeronautics, so right away there is strong evidence that firms involved with aeronautical R&D are not operating in a traditional free market. Additional columns in Table 4-1 have been added to examine the other segments. In foreign military sales, which account for another 11 percent, there are multiple customers but all sales are channeled through and controlled by the U.S. government. The recent failure of the Northrop F-20, an advanced fighter developed using $1.5 billion of private funds, illustrates the extreme risks posed by private development and the difficulty a truly private venture faces in competing with government-sponsored alternatives.

Foreign commercial sales account for another 30 percent. These are more representative of, but still are far from, a free market. Many of the foreign customers are nationalized airlines who can purchase equipment only with the approval of their governments. Likewise, most important foreign aircraft producers are themselves nationally owned. In such a situation, politics inevitably plays an important role, as illustrated by the recent purchase of airliners by India. In 1984 Indian technical committees recommended the purchase of the Boeing 767 for Air India and the 757 for domestic Indian Airlines (both government owned).[171] A few months later, Air India chose the Airbus A-310 and Indian Airlines chose the Boeing 757. Then, in September 1985, Indian Airlines cancelled their agreement with Boeing and signed for Airbus A-320s. It was widely reported that the Indians selected Airbus because they had recently selected MiG fighters over the French Mirage and they wanted to balance it with a purchase from the French.[172] This example represents the complex entanglement of financial and political considerations when government-owned buyers and sellers interact.

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170 Gansler, *The Defense Industsy*, p. 69.

171 *The Economist*, March 17, 1984, p. 74.

172 *Ibid.*, September 1985.

Table 4-1. Departures in Aeronautics Market from Classical Free-market Theory
(Adapted from Jacques Gansler, The Defense Industry)

Free Market Theory	U.S. Military	Foreign Military	Foreign Commercial	Domestic Commercial
Many small buyers	One buyer (DoD	Must go through DoD	√, but many nationalized	Few dominant firms
Many small suppliers	Few, large suppliers	←	←	←
All items small, divisible	Large, integrated items	←	←	←
Large quantities	Small quantities	←	←	←
Market sets prices	Monopoly pricing	√	Set by foreign government	√
Free movement in and out	Extensive barriers	←	←	←
Prices set by marginal costs	Proportional to total cost	←	Set by competition	√
Prices set by marginal utility	Any price paid for set performance	←	Prestige	√
Prices fall w/reduced demand	Prices rise w/reduced demand	←	←	←
Supply adjusts to demand	Large excess capacity	←	←	√
Decreasing/constant returns to scale	Increasing returns	←	←	←
Market shifts rapidly to changes	7-10 year development time	←	←	←
Market reaches equilibrium	Cyclic	←	←	←
Profits equalized across economy	Wide variations	←	No profits by foreign comp.	←
Perfect mobility of capital	Heavy debt, difficulty borrowing	←	Government financed	←
No government involvement	Regulator, specifier, banker, judge	←	Owned by government	FAA, CAB, EPA, OSHA
Selection based on price	Politics, negotiation	←	←	√
No externalities	Extensive regulation	←	←	←
Products of given type are same	Essentially, each different	←	√	√
Competition is for share of market	Frequently, all or none	←	√, but orders quantized	√
Production is for inventory	Production after sale	←	←	←
Size of market established by buyers and sellers	Third party (Congress)	←	√	√
Equal technology through industry	Competitive technologies	←	√	√
Benefits of purchase go to buyer	"Public goods"	←	√	√
Buyer has choice of spending now or saving for later	DoD must spend this year	←	√	√

Finally, one is left with domestic commercial sales. In 1985 these accounted for less than 10 percent of total aeronautical sales, so it is unclear that even if this segment operated completely as a free market it would have much effect on the incentives and behavior of the private manufacturers. As we see in Table 4-1, however, even in this area there are important exceptions that call into question the degree to which market forces can be expected to prevail. Among the most important characteristics of the transport market are that only a few large producers exist, with very high barriers to entry and exit, and that sales opportunities are grouped into a few very large orders spaced many years apart. The fact that development of a new aircraft may exceed the net worth of the company has led to the concept of "betting the company" on each new product.[173]

4.3 PRIVATE INVESTMENT IN AERONAUTICAL R&D

With the arguments of why the private sector may underinvest even in a free market, and the departures from a free market now clearly stated, we turn to the issue of whether such underinvestment does indeed exist. Figure 4-2 shows the rate of R&D spending as a fraction of sales, and suggests that the aerospace industry has, as a whole, consistently invested more of its own financial resources (between 150 percent and 200 percent) into R&D than the national average for all manufacturing.[174]

When government spending is included, total investment in aerospace R&D has averaged about 16 percent of sales. It is sometimes proposed that the private sector should be responsible for aeronautical R&D funding. This seems unlikely, however, given the magnitude of the gap between total R&D spending and private R&D spending, plus the fact that (as Figure 4-3 shows) the average profitability of the aerospace industry has historically been slightly *lower* than for manufacturing in general. It seems unrealistic to believe that the private sector could fully replace the government component should the government decide to stop all aerospace R&D funding. The choice is between providing government funding or accepting the societal consequences of lower investment.

These are all very general conclusions, but they set the stage for the examination of more specific cases that follow. We begin with the case most closely related to the free market, cases where the R&D at issue has potential benefits to the private sector.

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173 For a graphic description of this process, see John Newhouse, *The Sporty Game* (Knopf, 1984).

174 The data presented in this section are for the *aerospace industry as a whole*, and thus include space and missile work along with aviation. Separate data for aeronautics alone are not available.

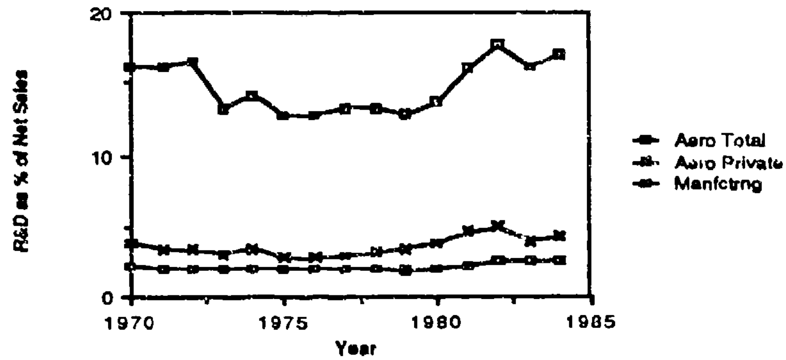

Figure 4-2. Expressed as a percentage of sales, R&D expenditures in aerospace are high relative to the national average for all manufacturing. The private sector share of funding in aerospace is consistently greater than the national average for all manufacturing, while the total percentage of sales devoted to R&D is more than four times the national average. The difference between private funding and total spending is met by public funds.

Source: Aerospace Industries Association, *Aerospace Facts and Figures 1986-1987*, p. 118. The AIA data are adapted from the National Science Foundation.

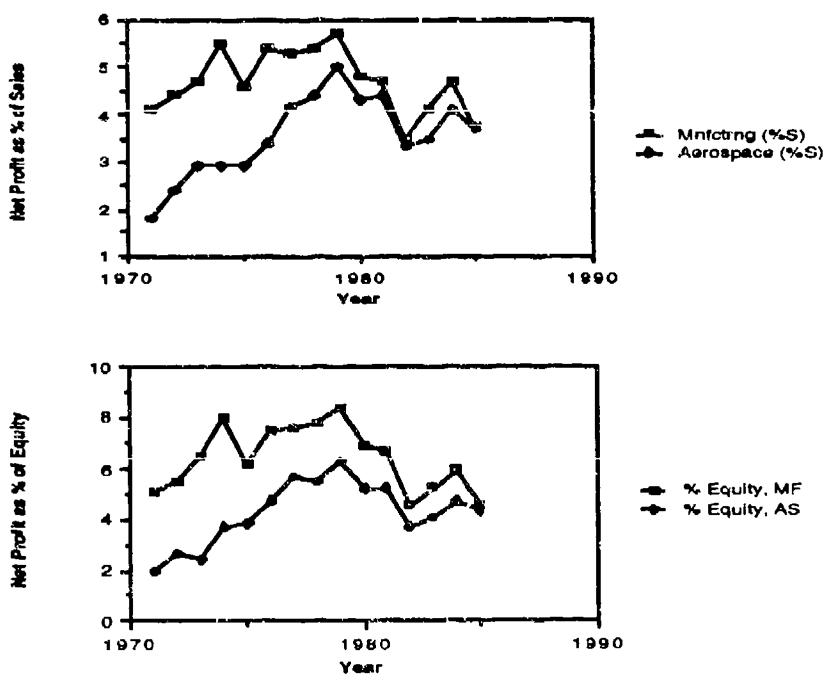

Figure 4-3. Net profit after taxes as a percentage of sales and equity for the aerospace industry and the national average for all manufacturing corporations. Historically, the profitability of aerospace has been slightly below the national average,which suggests that the industry would not be able to increase substantially its spending on R&D without impacting its ability to attract capital.

Source: Aerospace Industries Association, *Aerospace Facts and Figures 1986-1987*, pp. 168 and 169. The AIA data are adapted from Bureau of the Census reports.

CHAPTER 5. GOVERNMENT-SPONSORED AERONAUTICAL R&D WITH PERCEIVED PRIVATE SECTOR BENEFITS

The conclusion that in a free-market economy, government investment in R&D may be justified to compensate for private sector underinvestment, particularly in basic research, has sometimes been turned around and used as an argument that the government should invest *only* in basic research. In 1981, for example, the Office of Management and Budget (OMB) endorsed basic research but declared:

> [NASA] Technology development and demonstration projects [in aeronautics] with relatively near-term commercial applications will be curtailed as an inappropriate Federal subsidy.[175]

OMB based their arguments on the assumption of a free market which, as Chapter 4 has shown, barely exists in aeronautics. This chapter examines the general class of situations where economic incentives drive public and private-sector decisionmaking in common directions. As outlined in Section 1.3, there are four specific categories of interest, including cases where:

- private and public incentives are high, but joint action is required;
- both private and public incentives are high, and joint action is not required;
- private incentives are high, public incentives are low but joint action is required;
- private and public incentives are low when considered separately but high when considered together.

All of these cases share certain common features. In particular, all imply the ability to define and measure incentives, while distinguishing between public and private costs and benefits. The literature discussing cost-benefit analysis (CBA) and how alternative programs should be compared is extensive. This is particularly true in the case of private-sector decisions, where there is general agreement on the relevant measure of effectiveness,

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175 Office of Management and Budget. *Fiscal year 1983 Budget, Special Analysis K, Research and Development*, Government Printing Office, 1981.

namely, financial profit.[176] The literature on public-sector CBA is equally abundant but somewhat more controversial, due primarily to the difficulties of defining what constitutes "public goods" and how they should be measured.[177] The cases of interest here require both types of CBA as well as an integrated analysis that I will call "cross-sectoral CBA." The literature here is far more sparse,[178] and in the specific area of aeronautics it is virtually nonexistent.

The analysis that follows is built around two case studies. The first is drawn from the Short Takeoff and Landing (STOL) case study of Section 3.2. The second, more recent example examines one component of NASA's Aircraft Energy Efficiency program, the Advanced Turboprop (ATP). The normative and prescriptive analyses that follow these cases suggest that of the four categories mentioned above, the fourth one is by far the most important. They suggest that when the private sector considers its economic incentives to be positive, they are unlikely to be influenced or dissuaded by government R&D programs. Most "requirements" for joint action reflect technical, economic, or institutional uncertainty in the private sector's calculations more than absolute barriers. In areas where public-sector benefits would accrue from private sector activities, it may be a rational government strategy to assist in lowering the uncertainty in order to encourage the private sector. Sometimes this can be accomplished through operational demonstrations or direct subsidies, neither of which requires much government R&D. Frequently, however, an extensive research and development program is required. As a rational investor, the government should vigorously pursue such opportunities, as far as required to transition the program into private sector efforts while still maintaining a positive return on the government's investment. Planning and managing such programs is difficult, but successful examples do exist, and greater use of quantitative analysis techniques as planning (as opposed to marketing) tools would seem to offer important benefits to NASA.

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176 As an example of private-sector decisionmaking, see U.E. Reinhardt, "Break-even Analysis for Lockheed's TriStar: An Application of Financial Theory," *Journal of Finance*, Volume 28, Number 4, September 1973. For a general description see Thuesen, Fabrycky, and Thuesen, *Engineering Economy* (Prentice-Hall, 1977).

177 See R. H. Haveman and J. Margolis, *Public Expenditure and Policy Analysis* (Houghton Mifflin, 1983).

178 See Jeffrey Carmichael, "The Effects of Mission-Oriented Public R&D Spending on Private Industry," *The Journal of Finance*, Vol. XXXVI, Number 3, June 1981. Carmichael uses a capital asset pricing model and concludes that each dollar of government R&D funding adds around 92 cents to total R&D, crowding out private investment by as little as 8 cents to the dollar. His arguments are general and take no account of specific conditions in aeronautics.

5.1 AN ANALYSIS OF THE STOL RESEARCH PROGRAM

The government initiative to develop STOL aircraft as a means of offloading the conventional air transportation network has been discussed in Section 3.2. This section uses simple investment concepts to construct cost-benefit analyses as they might have appeared to both the private sector and the government in the early 1970s. The result illustrates how government investment in research can make an otherwise infeasible venture attractive to the private sector, with economic gains for both.

Four simple cases are examined, using estimates of costs and benefits as reported in the 1971 Civil Aviation R&D (CARD) Policy Study.[179] The first case examines the investment incentives for a private company to develop and produce a STOL transport assuming that the technology is well developed prior to starting the program. The second case examines how those incentives change if the private sector must also conduct a research and technology phase preceding the actual development. The third and fourth cases examine the government's incentives to finance the R&T phase, with two methods of determining public benefits. Following an illustration of the sensitivity of the results to projected growth rates, simple tests are suggested to provide guidance to R&D planners on when to start or stop government research programs.

Case A. Private Development of STOL. The CARD study forecast short-haul passenger traffic to grow from about 75 million passengers in 1969 to about 350 million in 1985 if an appropriate STOL aircraft was available.[180] We can estimate the number of aircraft needed to meet the increased demand using other NASA numbers and the simple equation:[181]

$$N = L\,D/(U\,S\,R\,P)$$

where:		
	N = number of aircraft required	
	L = lift capacity required	= 275 m/year = 753,000 px/day
	D = average stage length	= 275 miles[182]
	U = utilization	= 12 hr/day
	S = block speed	= 300 mph

[179] See *Joint DoT-NASA Civil Aviation Research and Development Policy Study, Report* (NASA SP-265, March 1971), and *Supporting Papers* (NASA SP-266, March 1971).

[180] *CARD Study*, SP-266, p. 2-4.

[181] See Robert W. Simpson, Notes for 16.751 course in Flight Transportation.

[182] *CARD Study*, SP-266, p. 3-13.

R = reliability = 95%

P = payload capacity = 100 passengers.

From these numbers it appears that about 600 STOL aircraft would be required. Total sales were forecast as $8.5 billion, implying an average price of about $15 million per aircraft. Development costs were estimated at $1 billion,[183] which I assume would be spread evenly over five years with the program priced to break even in five years after 300 sales.[184] The burden of development costs which must be recovered from each sale varies with the real interest rate as shown in Figure 5-1. Using a real interest rate of 6 percent (typical for the period in question),[185] about $4.5 million is required from each sale. This is a relatively large fraction of the selling price (about 25 percent), and whether or not it is obtainable depends on how much competition exists at the time of the sale (this is probably an upper limit). Production is continued at the same rate for another five years, with the sales revenue that previously went to amortize development costs now used to provide a profit for the manufacturer. A sample calculation is shown in Table 5-1.

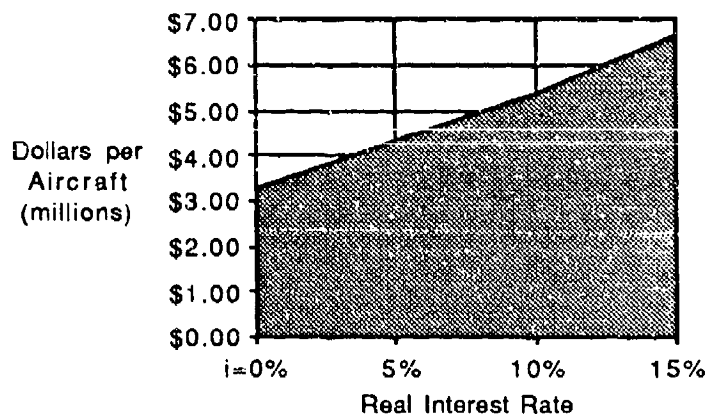

Figure 5-1. Revenue required from each sale in order to amortize STOL development costs of $1 billion spread over 300 units, as a function of real interest rate.

183 *CARD Study*, SP-266, p. 6-21.

184 These are reasonable numbers based on recent programs.

185 *Economic Report of the President*, 1982, Table B-67, p. 310.

Table 5-1. STOL Economic Analysis

Typical spreadsheet used to calculate the data in Tables 5-2 through 5-4. All cases assume a 10-year STOL R&T program, followed by 5 years of product development and a 10-year production program.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
2	Real Interest Rate:	6.00%																
3	Sales Price per a/c:	$15.00																
4	Direct labor:	50.00%																
5	Markup:	25.00%																
6	Ave. labor tax rate:	15.00%																
7																		
8	Years from Launch:			-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	1	2	3	4	5
9																		
10	Research Costs			($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)					
11	Development Costs			$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	($200)	($200)	($200)	($200)	($200)
12	# Units Produced			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Production Cost															$0		
14	Sales Revenues																	
15																		
16	Time Savings																	
17	Tax Revenues			$2	$2	$2	$2	$2	$2	$2	$2	$2	$2	$15	$15	$15	$15	$15
18		NPV:	IRR:															
19	Private: Production Only	$395	12.01%											($200)	($200)	($200)	($200)	($200)
20	Private: Production & R&D	$37	6.62%	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($200)	($200)	($200)	($200)	($200)
21	Public: Time savings only	$634	14.87%	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	($25)	$0	$0	$0	$0	$0
22	Public: time + taxes	$809	17.48%	($23)	($23)	($23)	($23)	($23)	($23)	($23)	($23)	($23)	($23)	$15	$15	$15	$15	$15
23																		
24	Net cash flow, Case A:													-200	-400	-600	-800	-1000
25	Net cash flow, case B:			-25	-50	-75	-100	-125	-150	-175	-200	-225	-250	-450	-650	-850	-1050	-1250
26	Net cash flow, Case C:			-25	-50	-75	-100	-125	-150	-175	-200	-225	-250	-250	-250	-250	-250	-250
27	Net cash flow, Case D:			-23.13	-46.25	-69.38	-92.5	-115.6	-138.8	-161.9	-185	-208.1	-231.3	-216.3	-201.3	-186.3	-171.3	-156.3
28																		
29																		

	A	S	T	U	V	W	X	Y	Z	AA	AB
8	Years from Launch:	6	7	8	9	10	11	12	13	14	15
9											
10	Research Costs										
11	Development Costs										
12	# Units Produced	60	60	60	60	60	60	60	60	60	60
13	Production Cost	($675)	($675)	($675)	($675)	($675)	($675)	($675)	($675)	($675)	($675)
14	Sales Revenues	$900	$900	$900	$900	$900	$900	$900	$900	$900	$900
15											
16	Time Savings						$600	$600	$600	$600	$600
17	Tax Revenues	$51	$51	$51	$51	$51	$51	$51	$51	$51	$51
18											
19	Private: Production Only	$225	$225	$225	$225	$225	$225	$225	$225	$225	$225
20	Private: Production & R&D	$225	$225	$225	$225	$225	$225	$225	$225	$225	$225
21	Public: Time savings only	$0	$0	$0	$0	$0	$600	$600	$600	$600	$600
22	Public: time + taxes	$51	$51	$51	$51	$51	$651	$651	$651	$651	$651
23											
24	Net cash flow, Case A:	-775	-550	-325	-100	125	350	575	800	1025	1250
25	Net cash flow, case B:	-1025	-800	-575	-350	-125	100	325	550	775	1000
26	Net cash flow, Case C:	-250	-250	-250	-250	-250	350	950	1550	2150	2750
27	Net cash flow, Case D:	-105.6	-55	-4.375	46.25	96.875	747.5	1398.1	2048.8	2699.4	3350
28											

These assumptions produce the undiscounted cumulative cash flow shown in Figure 5-2. The net present value (cash stream discounted to date of program start) is about $400 million at the baseline interest rate of 6 percent. The internal rate of return is about 12 percent. Such figures would make private investment very plausible, although not certain. Actual decisions would include such considerations as the confidence in the growth projections, alternative investment opportunities, etc. The important point for government policy is that private investment is *not* precluded.

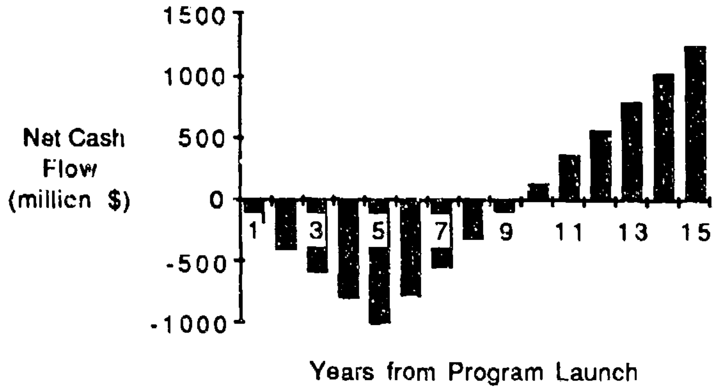

Figure 5-2. Undiscounted cumulative cash flow of basic STOL transport program as seen by private manufacturer. The calculation assumes a five-year development program costing $1 billion, and 600 sales in the following 10 years. The resulting internal rate of return is 12 percent. See Table 5-1 for supporting data.

Case B: Private Funding of Research. In 1970 no turbofan powered-lift STOL aircraft had even been flown, so no manufacturer was in a position to initiate a development program. A long-term research program was needed to develop and prove the technology. The CARD study estimated that such a program could cost between $10 million and $100 million annually.[186] Including this research program changes the net cash flow seen by the manufacturer to one resembling that in Figure 5-3.

[186] *CARD Study*, SP-265, p. 5-17.

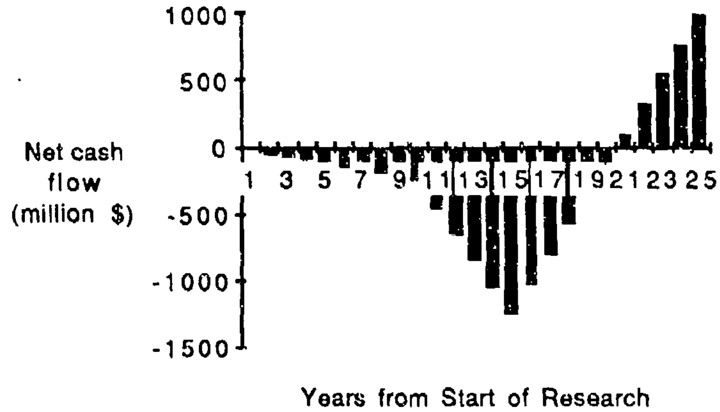

Figure 5-3. Undiscounted cumulative net cash flow seen if private manufacturer must fund ten-year research program prior to production decision. Research funding level shown is $25 million per year.

The attractiveness of the overall investment now depends on both the required research expenditure and the interest rate, as shown in Table 5-2:

Table 5-2. Internal Rate of Return and Net Present Value as a function of required annual research investment and real interest rate, for case where private manufacturer funds ten-year research program preceding development and production.

R&D Costs Per Year (million $)	IRR (%)	NPV (million $) 5%	10%	15%
$0	12.0	304	39	(27)
$10	9.1	227	(23)	(77)
$25	6.6	111	(115)	(152)
$50	4.1	(82)	(269)	(278)

The internal rate of return drops from 12 percent if no R&D is required to negative rates if $100 million per year is required. Real interest rates during the early 1970s were about 6 percent, which means that the STOL vehicles would appear economically attractive to private industry only if they required less than about $25 million per year in research and *if* the results of the research program could be counted on with certainty. Uncertainty as to the costs and outcome of the research program would further decrease its attractiveness to the private sector. One very rough measure of incorporating uncertainty is to calculate an average expected return; that is, the expected value if many similar R&D programs were conducted. For example, if the NPV of a successful R&D investment is estimated at $147 million, but experience has shown that the probability of success is only about 25 percent, then the effective NPV is reduced to (0.25) ($147M) = $36.7 million. Thus, the uncertainty drops the average expected IRR from slightly over 9 percent to about 6.5 percent. Accounting for the 75 percent of R&D programs that might be failures would further reduce the return; in fact, it would be negative if the full funding level was spent every time before a failure could be ascertained: (0.25) ($147M) + (0.75) (−100) = −$38M. It is easy to see why the private sector might be reluctant to embark upon such a program.

Case C: Government Funding of Research. The benefit stream seen by the private manufacturer of the STOL transport is entirely derived from the sale of completed aircraft. There are, however, other benefits besides sales revenues. Some, like the revenues these aircraft will earn while in operation, will be captured by other private companies. Other benefits accrue to society at large and do not appear in the economic calculations of private companies. For example, STOL aircraft were expected to provide benefits across the entire air transportation system by relieving traffic congestion and eliminating millions of hours of wasted time. The CARD studies estimated that these delays would cost between $600 million and $2 billion per year if a STOL system was not developed.[187] Strictly speaking, these benefits would accrue only to a percentage of the overall population (in particular, business travelers) but these benefits would not begin for at least fifteen years, making it impossible to identify, much less charge, the beneficiaries of the research at the time it was conducted. Such a situation is a classic argument for public funding of research. The public sector cost stream would then appear as in Figure 5-4, while the private cost stream then returns to that shown in Figure 5-1.[188]

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187 *CARD Study*, SP-265, p. 7-4.

188 I have not included potential disbenefits, such as noise to people living near STOLPorts, because the STOL transport as defined had noise levels comparable to urban background levels. If the noise standards were relaxed, such considerations would need to be included in the analysis.

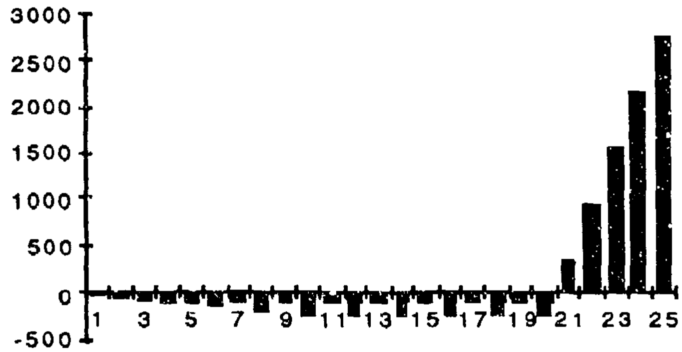

Figure 5-4. Undiscounted revenue stream projected if the government funds the STOL research program and realizes benefits from alleviation of congestion. For simplicity, the savings of $600M per year is assumed to begin after half the STOL fleet is deployed. The expected returns only accrue if the aircraft is actually built, so in practice they should probably be reduced by the expected probability of this occurring.

The value of this stream can be estimated as a function of required outlay and interest rate as shown in Table 5-3:

Table 5-3. Internal Rate of Return and Net Present Value as a function of research costs and interest rates, from public sector stream in Figure 5-4.

R&D Costs Per Year (million $)	IRR (%)	NPV (million $) 5%	10%	15%
$10	20.7	902	277	73
$25	14.9	786	184	(3)
$50	10.6	593	31	(128)
$100	6.4	207	(276)	(379)

The government's stream has lower outlays and longer payback times, but also larger benefits. Thus, funding a STOL research program appears to be an attractive investment even at discount rates applicable to the private sector. Many economists argue that the public discount rate should be lower than the private rate,[189] which would make the STOL investment even more attractive.

Case D: Tax Revenues from New Production. Counting the value of time savings that would accrue to the public is a rather broad way of defining government benefits. A more direct benefit (one not suggested in the CARD study) would occur in the form of income tax revenues on STOL aircraft production *if* the production occurs as a result of the R&D *and* would not have otherwise taken place *and* did not displace other programs (i.e., if it represented real economic growth, as indicated in CARD). Approximately 50 percent of the cost of a modern aircraft is attributable to direct labor charges, while the average tax rate in the American economy in the early 1970s was about 15 percent.[190] If only resulting tax revenues are counted in the government's benefit stream[191] (Figure 5-5), the STOL investment has an internal rate of return of 6.9 percent. (Table 5-4).

Sensitivity Analysis. Any analysis attempting to project both economic conditions and technology fifteen to twenty-five years in the future is obviously fraught with uncertainty. Let us examine but one example: the effect of traffic growth rate on the projected market size. As seen in Table 5-5 and Figure 5-6, a drop in the projected growth rate from 12 percent to 10% (a change of about −15 percent) would reduce the expected market size by almost 30 percent. The corresponding internal rate of return would fall by 38 percent (from 15.5 percent to 9.7 percent) and the net present value (at a discount rate of 6 percent) would drop by 66 percent, from just under $700 million to slightly over $200 million. Growth rates less than about 9 percent would make the program uneconomic at the 6 percent interest rate.

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189 See Chapter 33 of E.J. Mishan, *Cost-Benefit Analysis* (New York: Praeger, 1976). The basic argument is that government should take a longer-term view of society than should individuals, and should reflect this in the form of a lower discount rate. More directly, it is noted that investment rates set by the market include in them an anticipation of taxes, a factor that should not be built into social rates of discount.

190 *Economic Report of the President, February 1986.* Table B-23, p. 260.

191 If total public returns are counted (times savings + tax revenues) the values become:

R&D Costs Per Year (million $)	IRR (%)	NPV (million $) 5%	10%	15%
$10	24.1	1136	378	120
$25	17.1	1028	292	50
$50	12.8	850	150	(66)
$100	8.4	493	(134)	(298)

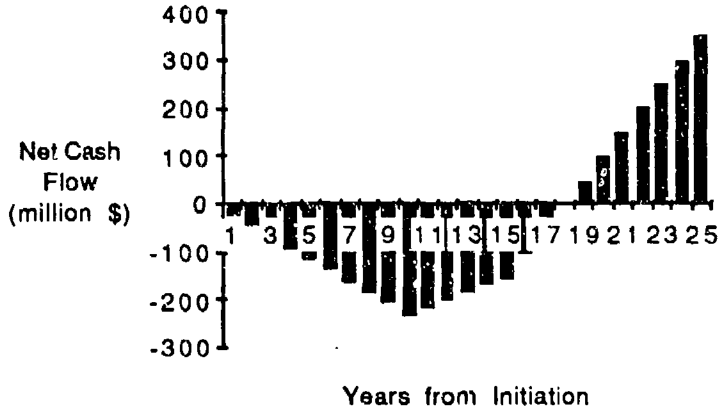

Figure 5-5. Undiscounted revenue stream if government funds research and then realizes tax receipts from new production stimulated by research. Data shown assumes R&D costs of $25 million per year and an interest rate of 6 percent. Internal rate of return is 6.9 percent, and net present value of cash flow shown is $21 million.

Table 5-4. Government Returns if only Benefits Are Tax Revenues

R&D Costs Per Year (million $)	IRR (%)	NPV (million $) 5%	10%	15%
$10	14.5	156	40	(3)
$25	6.9	49	(46)	(72)
$50	1.7	(129)	(188)	
$100	–	(486)		

Table 5-5. STOL market as a function of growth rate.

Growth Rate	1985 Traffic (billion px-mi)	STOL A/C Required	IRR (%)	NPV (@ i=6%)
0.00%	75.00	0		
2.00%	100.94	57		
4.00%	135.07	132		
6.00%	179.74	231	(1.94)	
8.00%	237.91	359	4.2	(100)
10.00%	313.29	525	9.7	230
12.00%	410.52	739	15.5	684
14.00%	535.35	1014	21.2	1261
16.00%	694.91	1336	27.1	1983

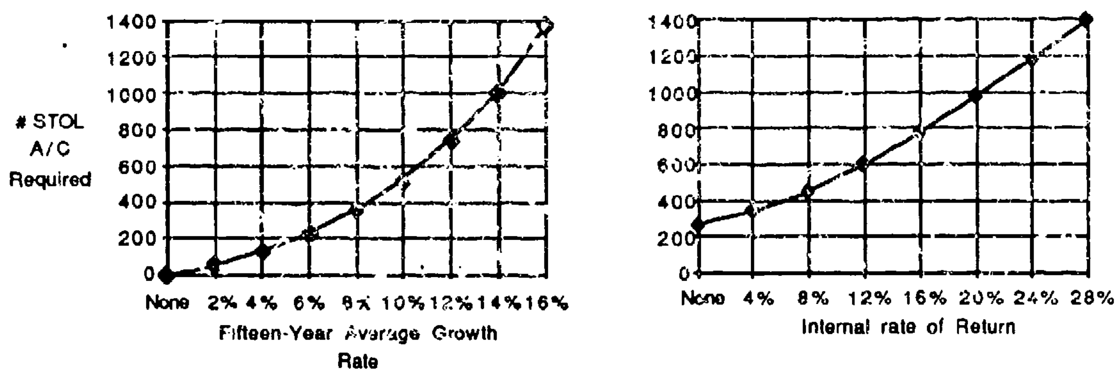

Figure 5-6. Sensitivity of STOL market to traffic growth rate. In 1970, the growth rate projected for the 1970-1985 period was 12 percent; the actual rate averaged about half that.

Actual results. In 1970 the Federal government was forecasting an $8.8 billion market for short-haul transports by 1985;[192] when that date passed not a single turbofan STOL transport was even in development. The most basic question for any analysis of the

[192] See *NASA Budget Estimate for FY 1972*, p. RD 10-2.

national STOL effort must be why these initial projections turned out to be incorrect. There exist three major possibilities: (1) the technology could not be developed; (2) institutional barriers existed that blocked its adoption; or (3) conditions changed in the marketplace that invalidated the initial analysis.

All of these are explored more fully in the case study, but the primary answer to the question of why STOL failed to develop appears in Figure 5-7. During the late 1960s planners were projecting total airline traffic at 400 billion passenger-miles for 1982; the actual figure was 259.[193] STOL planning grew out of an era when noise, pollution, and congestion in the air traffic control system were already causing serious problems; when combined with extrapolations of then-current growth rates the problem appeared to require drastic action. STOL was the linchpin of the government's proposed solution. Yet even as the CARD study was under way, factors were under way which made its forecasts invalid.

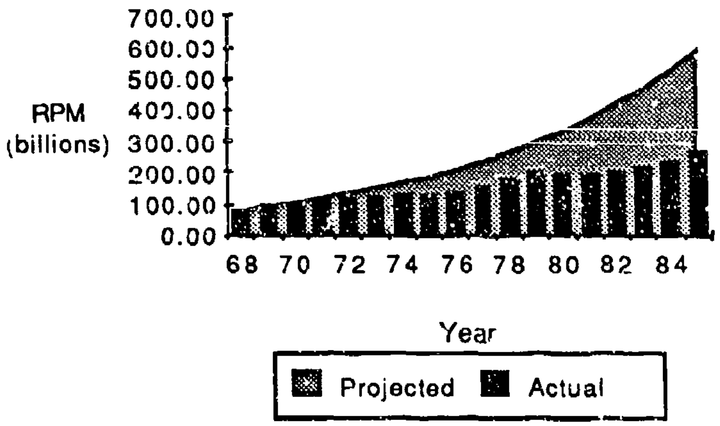

Figure 5-7. The primary reason that STOL failed to become a viable commercial proposition was that the traffic base projected in the CARD study has failed to develop, and with it, the anticipated congestion. (Source: Projections: NASA SP-265; Actual data: AIA *Aerospace Facts and Figures 1986-87*, p. 91.)

There are many contributing factors for the failure of the traffic base to develop as projected. The first was a serious recession in 1971. This cut traffic and, combined with the widebodies, led to extensive overcapacity in the airline industry. Not only did the

193 Aerospace Industries Association, *Aerospace Facts and Figures, 1986-87.*

traffic base increase much more slowly than projected, but congestion delays within the system dropped substantially. The introduction of widebody transports decreased the number of operations, while expansion of the existing ATC network made those operations more efficient. STOL depended on congestion in the CTOL system for its economic viability. Thus, the changes that occurred in the air transportation system during the 1970s worked against STOL even as NASA pressed forward with its research.

5.2 THE ADVANCED TURBOPROP PROGRAM

The STOL case study is an example of a civil research program where government involvement initially appeared to be justified, but later was terminated when it became clear that the private sector could not economically utilize the technology on the timescale originally envisioned. We now examine a second example, with similar origins but different results: the advanced turboprop program (ATP).

When the first generation of commercial turbojets was introduced in the late 1950s, there was doubt as to whether they would prove economically attractive due to their high fuel consumption. The increased productivity (due to size and speed) and the low maintenance requirements of the jets, plus the lower fuel consumption offered by turbofans, soon eclipsed propellers for all but the smallest passenger aircraft. "Propellers are for boats" declared Eastern Airlines as they heralded the all-jet Shuttle service. Yet the rapid rise in fuel prices (see Figure 5-8) during the 1970s provided strong incentives for improving the fuel economy of airliners. In 1975, NASA's Aircraft Energy Efficiency program identified turboprops, along with laminar flow, active controls, and composite structures, as an area where major advances in fuel efficiency were possible. Growing partly from their work on quiet propellers for general aviation aircraft and partly from their work on supersonic-tip compressors and fans, NASA proposed to develop a new class of turbine-driven propellers that would be capable of high flight speeds and turbofan-comparable maintenance.[194]

[194] The NASA ATP effort itself grew out of several earlier efforts. Some were in-house, such as the Quiet Propeller work supported by the EPA for general-aviation aircraft. Other work was done at Hamilton-Standard during the early 1970s.

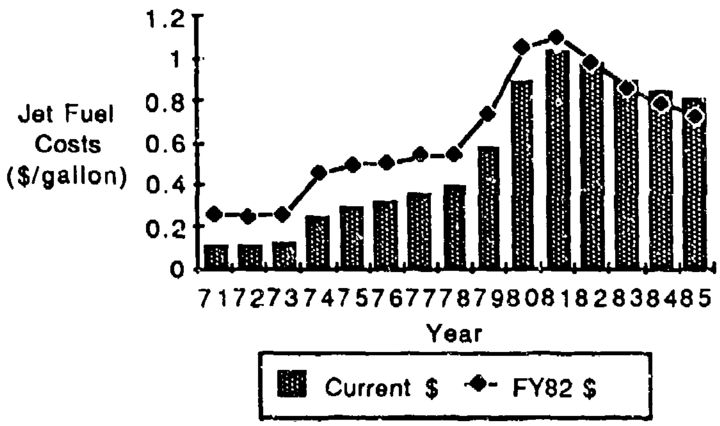

Figure 5-8. U.S. Jet Kerosene Prices, in both current-year and constant (1982) dollars.
Source: *Aerospace Facts & Figures, 1986-87*, p. 95.

In its initial analysis, NASA concluded that an ATP airliner might consume only half the fuel required for the then-standard medium-range transport. Although this savings was approximately equal to that from all the other proposed technologies combined, NASA recognized that these large benefits in fuel costs might not be enough to ensure commercial use of such technology if they were offset by manufacturing or maintenance costs or by other factors such as physical safety or noise. Thus, they extended their analysis to estimate the return on investment an ATP might provide not only to the companies that developed and produced it, but also to the airlines that operated it. They concluded that it was economically feasible for both parties to capture positive returns through an ATP. The NASA analysis stopped there, however, with no further discussion about why, if the returns looked so positive to the private sector, government involvement was justified at all. In this section I will briefly re-create the NASA analysis, and then extend it to consider the effects of the required research and technology development phase that NASA itself proposed, and has since undertaken.

The NASA methodology, developed at Ames in 1977, was labeled "ABC-ART," for Analysis of Benefits and Costs of Aeronautical Research and Technology.[195] In it, Ames researchers pulled together traffic data from the CAB, production cost models

195 See L.J. Williams, H.H. Hoy, and J.L. Anderson, "A Method for the Analysis of the Benefits and Costs for Aeronautical Research and Technology," in *CTOL Transport Technology, 1978*, NASA Conference Publication #2036, February 1978 (N78-29060).

developed by RAND, and operating cost models developed by MIT.[196] Assuming a 6 percent annual traffic growth rate and a 16-year aircraft retirement age, they calculated that approximately 870 new medium-range, wide-bodied aircraft suitable for propulsion with ATP would be required between 1987 and 1995.[197] Development and certification of the propulsion system was assumed to require 4.5 years and cost almost $500 million (in FY75 dollars); airframe development would require 3.5 years and cost $225 million. Total development costs would amount to $1.3 billion, with the first unit costing $34 million to produce.[198] The manufacturer's estimated cumulative cash flow is shown in Figure 5-9.

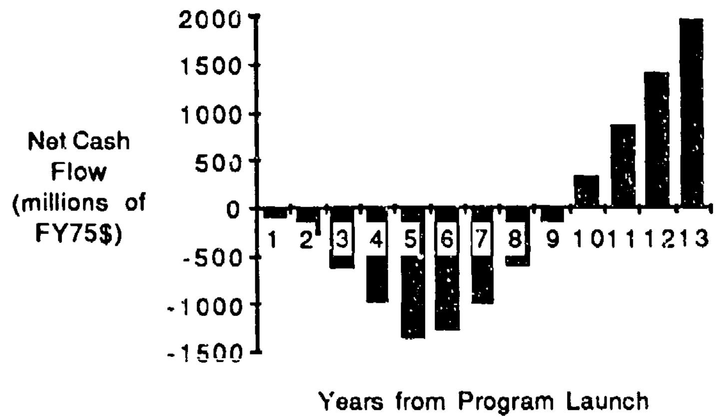

Figure 5-9. Estimated cash flow for manufacturer of an Advanced Turboprop Aircraft. Assumes 436 aircraft sold at $19 million apiece.

Airline operating costs were estimated using models developed by MIT, and airline return on investment was then plotted along with manufacturer return as a function of unit aircraft price (Figure 5-10). Sensitivity of airline return due to variations in yield were considered, as were two sizes of production runs. NASA concluded that sufficient incentives did indeed exist for the development of advanced turboprop aircraft if the technology was available.

196 J.C. Bobick, et al., *Documentation of the ABC-ART Models, Volumes 1 and 2* (SRI International Corp., Menlo Park, CA) July 1979 (N80-15865 and N80-15866).

197 In this 1975 study, it was assumed that no new medium-range aircraft would be introduced before the ATP, and that the B-727 would continue in production until then. The introduction of the B-757, 767, 737-300 and A-320 invalidated this assumption).

198 All values here are in 1975 dollars.

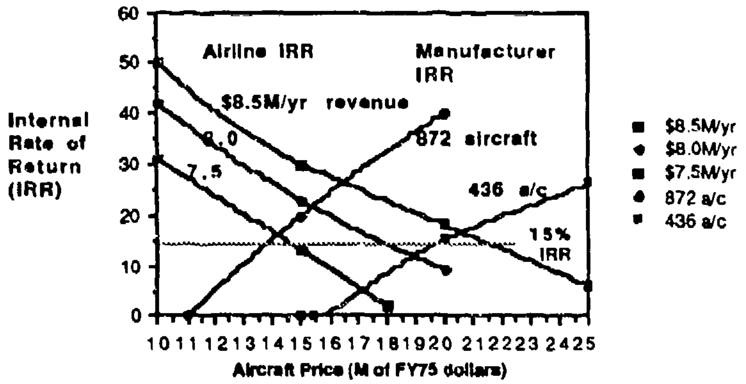

Figure 5-10. ATP manufacturer and operator return on investment, as function of yield, market size, and selling price of aircraft. The $8.0M/year revenue curve represents 1975 average airline yields. The 436 aircraft curve assumes that two manufacturers develop ATP aircraft and split the market.
Source: Williams, Hoy & Anderson, p. 884.

NASA's calculations did not include the research and technology development costs to develop turboprop technology to the point that a private go-ahead could comfortably be made. They assumed that the government would provide this funding, totaling about $200 million over 5 years.[199] The sections that follow examine first how the private sector's incentives would change if they themselves had to fund the preliminary research, and then, what public sector benefits might accrue from ATP research and development.

Private incentives to conduct ATP R&T. It is clear from Figure 5-10 that the manufacturer's incentive to develop an ATP is a strong function both of sales price and volume. Assuming that a manufacturer could capture half the market (436 aircraft) and that the aircraft was priced to provide equal returns to the airline and to the manufacturer at then-current airline yields, each aircraft would sell for about $19 million. The internal rate of return would be about 12 percent. The NASA numbers excluded all R&T costs. If these costs had to be borne by the private sector, the cash flow seen by the manufacturer would become that in Figure 5-11. The exact rate of return would then depend on the cost and duration of the R&T program. In its 1975 study, NASA apparently assumed that 8 years would be required; internal rate of return as a function of R&T cost would then vary as shown in Figure 5-12. Including R&T costs thus changes an apparently favorable investment into one that is much more ambiguous. Financial breakeven is now projected

[199] See *FY83 Senate Authorization Hearings*, p. 551, February 1982.

twenty years after start of the program. Considering the uncertainty over whether the R&T would be technically successful and whether it would be environmentally or aesthetically acceptable,[200] it is easy to understand the private sector's reluctance to undertake ATP work in 1975.[201]

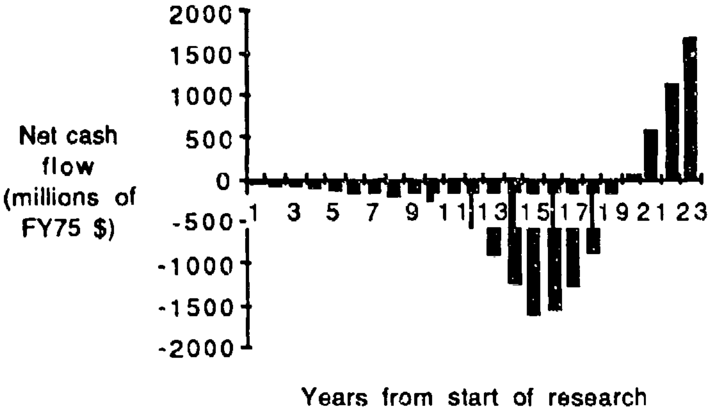

Figure 5-11. Manufacturer's net cash flow if R&T costs for ATP technology are included. Assumes $25M/yr in R&T at 6 percent interest rate.

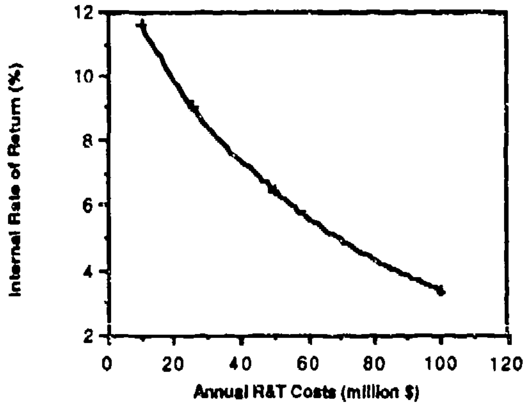

Figure 5-12. Private sector's internal rate of return as a function of ten-year average R&T cost. At a discount rate of 6 percent, the ATP would appear attractive only if it required an investment of less than $50 million per year.

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200 Technical issues included: blade safety and reliability, use of a gearbox, use of one set of blades or two counterrotating sets, etc. The primary environmental issue was noise, especially internal noise. The passenger acceptance issue is somewhat more dubious (countered by the arguments that passengers would fly an ATP if it was cheaper) but nonetheless was widely made.

201 Established propeller manufacturers like Hamilton-Standard had begun preliminary ATP studies even before NASA, but in general the major manufacturers (GE, P&W, Boeing, Douglas) were dubious and did not endorse the initial NASA proposals.

Public incentives. That private incentives to use the technology are high if it is provided by NASA is not in itself a case for government funding of projects like the ATP. The question of public returns, both positive and negative, must also be addressed. The primary potential disbenefit would appear to be noise. Since the noise level of an ATP was one of the aspects to be evaluated during the research, noise could not be used as either a positive or negative consideration at the beginning.[202] The three public benefits most commonly proposed to justify government support of ATP were employment, foreign competition, and fuel savings. The employment arguments depend on whether an ATP would represent a net increase in production or whether it would displace production of a turbofan. ATP could be used to offer a competitive advantage on the international marketplace; there was also the possibility of a massive loss of engine market (and hence, employment) to a foreign competitor should they develop a viable ATP rather than the United States. Since both of these considerations involve extremely large uncertainties, however, fuel savings has been the primary public benefit upon which programs such as ATP are evaluated.

NASA estimated that an ATP would save about 1.3 million gallons of fuel per aircraft per year as opposed to the 1975 standard, the Boeing 727. Thus at the 1975 fuel prices of $0.40 per gallon, ATP aircraft would save about $4 billion in fuel costs during the period they were being introduced. As shown in Figure 5-13, this amount does not reflect the full benefit generated by ATP, since an additional savings would accrue from the increase in traffic generated by the reduction in price. These benefits would be distributed between the manufacturers, the airlines, and the traveling public. It would be rational for any of these parties to invest in ATP R&D. The exact distribution would depend on the degree of competition present, the elasticity of the demand curve, and the shape of airline's marginal revenue curve. In a fully competitive situation the consumer's surplus could reach 100 percent. What is needed is some mechanism for capturing some of the consumer's surplus that would occur from ATP development, and reflecting that in the cost-benefit calculations.

202 There were good technical arguments that a turboprop could be either quieter or louder than a turbofan to ouside observers. The primary problem is internal noise.

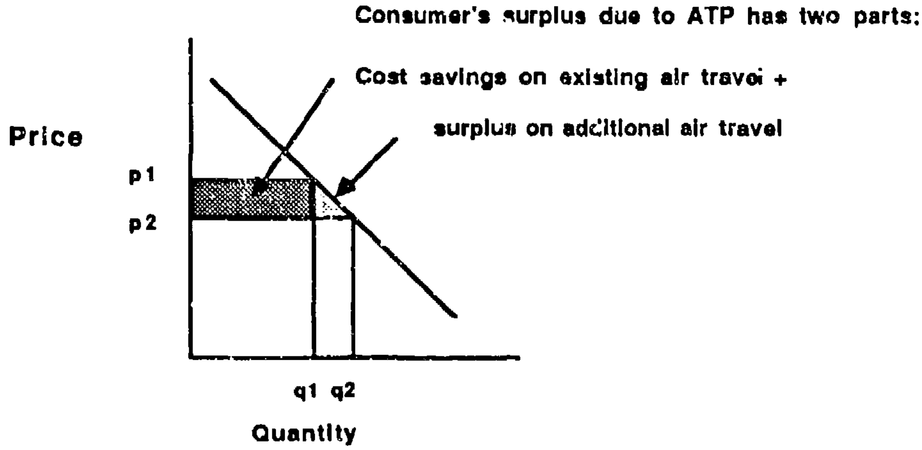

Figure 5-13. If the development of ATP resulted in lower fares, a "consumer's surplus" would result. This net public benefit would not be included in any private calculation of the benefits of ATP. This would be a rational investment if some mechanism existed to collect part of this surplus from the traveling public and use it to fund ATP research. NASA has used general tax revenues as a surrogate for direct taxation of travelers.

A good case could be made that some form of a ticket tax would thus be appropriate to fund this type of R&D. Lacking such an arrangement, funding the investment from general revenues is a second-best solution. (To NASA, which has no charter in devising tax policy, the traveling public is a subset of the taxpayers in general, and as a first-order approximation, the benefits of fuel savings are returned to the taxpayers.) An additional argument, less quantifiable but more defensible, is that national security benefits are also realized through reduced fuel consumption, by lessening U.S. dependence on imports, saving funds that would otherwise go overseas, or prolonging domestic energy supplies. Again, a proper consideration of these issues is outside of NASA's charter, falling instead to the Departments of Energy and Transportation, and they apparently did not play a major role in the ATP justification.

If the government funded the R&D and then realized half the total benefits from the fuel savings, its cash flow would be that shown in Figure 5-14. Note that in this stream the government realizes the benefits from the entire ATP fleet, whereas a manufacturer sees only the benefits of his company's share of the sales. Further, the government's returns continue for as long as the aircraft are in operation. On the other hand, the government cannot count the total difference between ATP and the aircraft it replaced, but only the difference between the ATP and an equivalent turbofan-powered replacement.

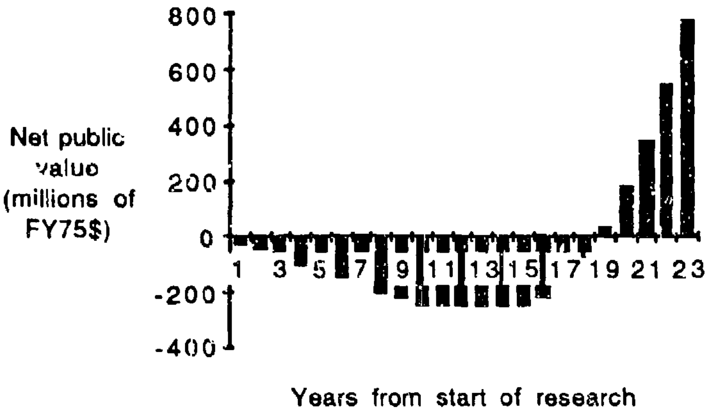

Figure 5-14. Net value flow to public sector if government funds ATP R&T and then realizes benefits of fuel savings. Fuel cost $0.40 per gallon.

The benefits of ATP should extend over the full lifetime of the engines. It is probably unfair to credit the NASA calculation with all these benefits, however, since the ATP would probably be developed eventually, by either a manufacturer or by a foreign competitor. Thus, the benefit stream in Figure 5-14 counts only the first ten years.

Sensitivity Analysis. The government's return varies as a function of both R&D costs and of fuel price as shown in Figure 5-15. By plotting the private sector's expected return on the same figure, it is possible to compare which sector has the highest incentive to undertake ATP research. At fuel prices of $0.40 per gallon neither the public nor the private sector has much incentive to undertake ATP research; the government's incentive is higher only if the research can be accomplished for less than about $25 million per year. While the private sector's dependence on the price of fuel is small, the government's return is very sensitive: at a price of $0.80 per gallon the government always has higher incentive than the private sector.

Development of the ATP. The original ACEE plan envisioned ATP as a four-phase program, concentrating first on propeller technology, then structures and composite design, then a phase of experimental engine tests, and finally, flight demonstrations. At the time the cost-benefit calculations were made, only the relatively inexpensive R&T work on propeller technology had been approved. Since then, at least three large experimental programs have been undertaken, including the: (1) *Large-scale Advanced Propfan (LAP)*, a four-year program with Hamilton Standard involving tunnel testing of 2-ft-diameter

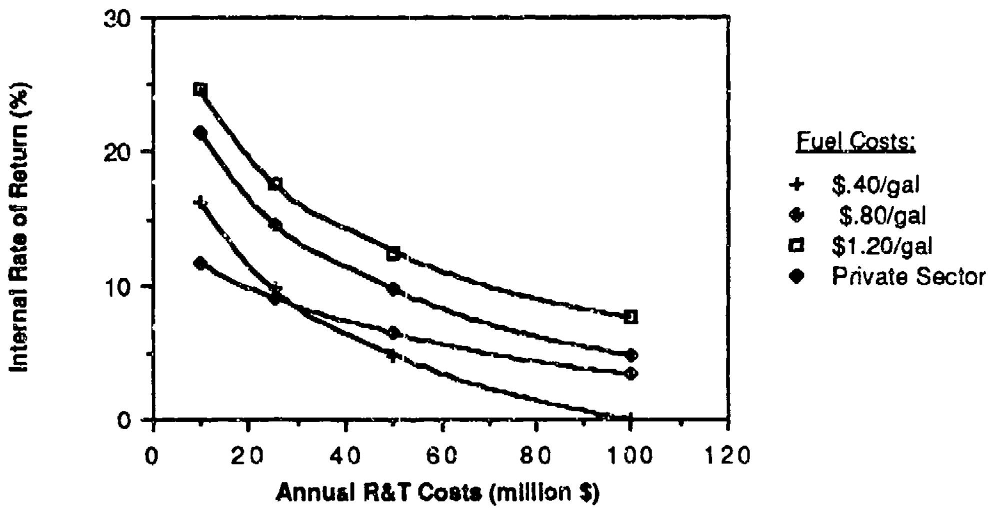

Figure 5-15. Sensitivity of returns to fuel price and ten-year averaged R&T costs. The public sector returns depend on the price of fuel, the manufacturer's returns (to a first approximation) do not.[203]

single-rotation propfans; (2) *Propfan Test Assessment (PTA)*, involving flight tests of an eight-blade, 9-foot diameter Hamilton Standard fan on a Gulfstream II by Lockheed-Georgia; and (3) the *Unducted fan (UDF)*, a General Electric concept for a gearless ATP using two counter-rotating propellers. The turning point for ATP probably came in 1983, when General Electric announced that it would go ahead with a 12-foot diameter, 25,000 pound thrust "unducted fan" powered by an F404 engine core. Assisted by $27 million in NASA funding, this engine ran for the first time late in 1985.

At the time of this writing, it is too soon to determine what the commercial outcome will be, and hence, whether or not public returns will be realized. In one very important sense, however, ATP is already a success for NASA, in that it has stimulated major private-sector investment in an area that might have gone largely unexplored without government involvement. Significant private investment is now taking place. Boeing flew a UDF on a 727 in 1986, and McDonnell-Douglas plans to fly one on an MD-80 in 1987. Both companies are actively pursuing aircraft for introduction in the early 1990s. The slippage of about six years from the 1975 NASA ATP projections is due in large part to the

203 In the calculations made here, there was no dependence by the numbers of units sold on the cost of fuel.

introduction of new turbofan aircraft in the late 1970s and the leveling off of fuel prices during the 1980s (even the recent drops in cost still leave the real cost of jet fuel at twice its 1975 level; see Figure 5-8).

NASA, meanwhile, must now face the paradox of a successful civil program: even as the propfan program gathers momentum (and publicity) there are strong arguments that the NASA effort should wind down. This is because the whole idea of the NASA program was to advance the technology to the point where the private sector could take it over; once this happens the justification for continued NASA efforts must be reexamined.

5.3 LESSONS FROM STOL AND ATP

In the late 1960s STOL was frequently presented as an attractive opportunity for the private sector if only the government would remove such "institutional constraints" as noise, air traffic control, or bureaucratic inertia.[204] The analysis in Section 5.1 confirms that STOL was a case where private incentives were indeed low if R&D costs were included, but *conceivably* could be made very attractive if suitable powered-lift technology was available and if congestion continued to develop as projected. The magnitude of the projected return from the STOL program to the public sector depended on whether "public benefits" were defined broadly (accruing to society but not captured by the private sector, e.g., time saved) or narrowly (resulting in increased government revenues, e.g., from tax benefits of new production), but both definitions indicated a net positive return to the government from a successful program. Thus, NASA's decision to initiate a focused effort in STOL technology was indeed justifiable by the investment criteria proposed here.

Unfortunately, NASA never defined the appropriate government strategy explicitly in terms of stimulating the private sector. Thus, once the STOL program was initiated, NASA failed to track the private sector's incentives and how they were changing. During the early 1970s, these incentives were decreasing, not growing larger as the NASA program assumed. NASA's failure to perceive this, and to consider it in their planning, led to three mistakes that together resulted in the STOL research program failing to meet its policy goals.

The first mistake was to press forward with the overly ambitious QUESTOL program. As a major demonstration program, QUESTOL clearly required the participation

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204 *CARD Report*, p. 6-3.

of the private sector. When proposals for cost sharing fell through, NASA should have recognized that the private sector's uncertainty did not warrant this stage or size of program, and scaled it back accordingly. Instead, NASA allowed the program to continue for almost two years before OMB intervened and abruptly killed it. This delay led to the second mistake, which was the timing of the QSRA. QSRA was an example of a cost-effective, technically successful "proof-of-concept" research aircraft, but it came too late to have an impact either on the civil or the military STOL efforts. Much of this delay is attributable to QUESTOL. Because it was late, QSRA had far less impact than it probably deserved. This in turn led to a third major mistake, which was the termination in 1978 of all R&T Base activity related to STOL. QSRA continued to fly, but the long-term effort was pulled out at the roots. This precluded precisely the type of ongoing R&T effort that would allow future programs to be organized as conditions warranted.

The Advanced Turboprop, on the other hand, appeared to have few if any "institutional roadblocks." Any aircraft manufacturer that could offer its customers a 25 percent advantage in fuel burn would surely have a competitive advantage. Yet even here, as the analysis in Section 5.2 demonstrated, when R&D was included in a private cost-benefit analysis, turboprop research had low incentives especially when compared to other, near-term choices. That the private incentives were perceived to be low is confirmed by the lukewarm response given to ATP by industry representatives when it was initially proposed.

In contrast to STOL, however, ATP is an example of a case where NASA moved in step with the market and, as a result, successfully transitioned its work to the private sector. By 1983 General Electric was investing heavily in its version of the ATP, the Unducted Fan. By 1986 a flight demonstrator version of the engine had been flown on a Boeing 727, with similar joint tests planned between GE and McDonnell-Douglas on a DC-9. The entire UDF effort grew out of ATP, but once it had passed a critical point within the private sector, the private effort accelerated rapidly and diverged from the original NASA program. This suggests that government R&D investment does little to discourage or displace private investment. Once the private sector perceives its economic incentives to be positive, it acts much more independently.

The successful transition changed (but did not entirely remove) the motivation for government involvement. Much of the private sector's investment in the UDF, for example, was aimed at development of specific, marketable products. Having stimulated this private investment, NASA must now complement the private sector's investment.

First, it must continue to investigate alternative strategies. ATP is not yet a commercial success, and it may yet be stymied by reliability, noise, or other factors not yet fully understood.[205] The government will not realize its benefits until the engines are actually in use, so it is prudent for the government to hedge its bets through the continued investigation of alternative concepts. Second, it should promote efficiency, by taking advantage of private sector developments and tests to accumulate data. If left to the private sector, much of the available data would either not be collected at all, or they would never be disseminated in a way that made them available for future research. Third, the government should stimulate competition among producers. The share of benefits passed on to consumers depends on competition among suppliers (a monopolist could appropriate much of the value of the research himself) so, to provide the public benefits necessary to justify its investments, NASA has an interest in promoting or maintaining competition wherever possible. These arguments are clearly weaker than the ones that justified the program at its inception. They probably would not justify initiating a new program, but they do support continuing the existing role, with a gradual phase-down rather than an abrupt termination.

Thus, it appears that both STOL and ATP are examples of situations where, when faced individually with the entire R&D task, the incentives were small or ambiguous for the private sector. In both cases, public goods existed that were not appropriable to any private firm, and thus were ignored in their calculations. In neither case did these benefits alone justify government preemption of the private sector's entire role, but in both cases it appeared that a strategically-targeted partial investment might stimulate the private sector. Thus, by dividing the R&D program between them and sharing the costs, both the private and the public sector could capture their respective benefits and realize an attractive return on their investments.

The difference in outcomes between the two examples illustrates the variety of the roles the government can play and the criticality of timing in adopting these roles. Particularly in the early days, the government can take a leadership role. During this period, private-sector incentives are low, and this is likely to result in low approval ratings

205 Recent delay of the Boeing 7J7, a prime candidate to use the UDF ATP, is certainly a setback for the introduction of the ATP. McDonnell-Douglas continues to pursue the use of the engine on the MD-90 series, however, and the Boeing decision probably reflects the wisdom of the current institutional arrangement, where NASA supports technology but is not involved in development of specific products. It probably would have been much more difficult to stop the 7J7 had the government been involved.

or lukewarm response to the government proposals. As the situation develops and the private sector's incentives become more clear, however, the government role shifts first to sharing leadership, and eventually to a supporting role. If this transition does not occur the government must carefully examine what is going wrong. In the case of QUESTOL, for example, the private sector's refusal to engage in cost-sharing should have been a very strong signal to NASA that their program was overly ambitious and should be revised. On the other hand, when this transition occurs successfully, as it did with ATP, then the government's planned program is likely to be quickly outrun. In this case, the government must again reexamine its program and be prepared to adjust it accordingly.

In addition to the requirements for common costs but distinct and separable benefits, these cases share several characteristics. First, in each case a strong R&T base was a *prerequisite* for effective NASA response, not a response itself. In order to conduct cost-benefit trade-offs, enough must be known about the technology to at least identify the key uncertainties and begin to address them in a specific manner. NASA had some of the needed background in STOL because their STOL research dated back to the middle 1950s, and had been particularly active in the years before QUESTOL. Some R&T background for ATP also existed, primarily because of work initiated in the early 1970s in conjunction with the EPA studying means of quieting general aviation propellers. In neither case was the R&T base fully in place, and augmentation of the R&T base was necessary in each case (the ATP program was delayed two years by this requirement).

5.4 A GENERAL INVESTMENT PHILOSOPHY

What can now be said about the general case of aeronautical R&D that offers potential benefits to the private sector? This section attempts to draw together the methodological conclusions from the two examples and suggest strategies for dealing with each of the four categories introduced at the beginning of the chapter.

The evidence in this chapter is clear that a strategy based on pursuing only "technological opportunity" is not enough. To efficiently pursue its missions NASA must stimulate the private sector, and to couple private and public programs requires understanding not only the net incentives but the factors that determine those incentives. The appropriate government program must change in response to external changes. To recognize and assess these changes, cross-sectoral cost-benefit analysis (CBA) is a necessary and effective tool.

In both the examples studied here, NASA correctly used CBA to establish the potential of private sector benefits. In neither case did NASA take the necessary subsequent steps, of establishing why this potential was likely to remain unrealized unless the government took certain steps, primarily to reduce uncertainty through R&D, and why this government action was in turn likely to be fully justified by appropriable public benefits, separate and distinct from, but nonetheless coupled to and dependent on, the private sector program. Thus, NASA's use of CBA to date seems to have been more as a sales tool than as an instrument of rational planning.

In cases where NASA's decision was correct, it could have been more pursuasively made with full CBA. In cases where their decisions were not correct, this would have been evident sooner if CBA had been used. It is my contention that, although cost-benefit analysis is no panacea, it certainly can serve a useful role in both the planning and the execution of this type of government R&D program.

One of the primary arguments made against CBA is that it cannot handle the effects of uncertainty. Among the most important uncertainties are development time, the scale of investment required to achieve an R&D goal, the probability of achieving success, and the impact or likelihood of future changes in externalities (i.e., congestion in STOL or fuel price in ATP). Some of these uncertainties can be treated parametrically. Even if exact values cannot be known, boundaries can often be established, and the goal is broad guidance. Other uncertainties must be estimated as best as possible. As long as the calculations are updated periodically, the impact of these uncertainties can be updated and their impact progressively reduced. This use of CBA as a "closed-loop" management tool is essential. When programs are managed without feedback (as in the STOL case), the directions can go seriously wrong.

The type of quantitative approach being proposed is exemplified in Figures 5-16 and 5-17. Figure 5-16 summarizes the private sector's view of STOL in the late 1960s, with projected internal rate of return plotted against rate of R&D spending. In the case where no research was required, the expected IRR on the development and production program would be about 12.5 percent. The precise scope of the required R&D program is unknowable, but can be bounded. Curves are shown for 2-, 5-, and 10-year programs, with total costs of $100M, $500M, and $1 billion. Below some real interest rate (shown here as 6 percent) the investment is unattractive because its discounted net present values will be negative. In order for the private sector to undertake rationally a STOL development program they must have reasonable expectations that it can be accomplished for not much more than about $100M in R&T.

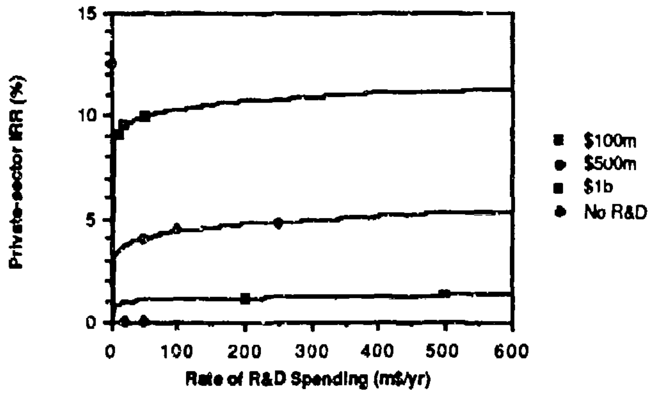

Figure 5-16. Internal Rate of Return as viewed by the private sector plotted as a function of required research investment for the STOL cases hypothesized above. To achieve internal rates of return of 6 percent or greater, the total required R&T program must cost less than about $300M.

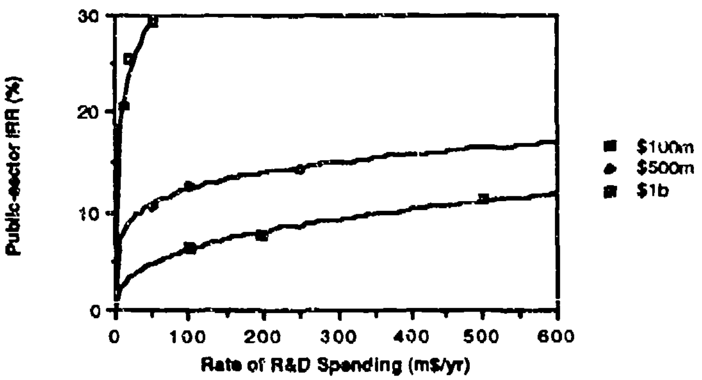

Figure 5-17. Comparable plot of public sector rate of return versus rate of R&D investment. Data shown are for STOL case.

Figure 5-17 shows the situation from the public sector's point of view. There are public benefits to be obtained through STOL that are not accounted for in the private sector's calculations. If the private sector built STOL aircraft without any government R&D investment, the government's IRR would be infinite: finite benefits with no investment. Clearly, the government's rational investment strategy is make the minimum investment required to trigger private sector activity. Looking back at Figure 5-16, there are two basic possibilities: it can either lower the real interest rate, or decrease the size of the investment involved. The first choice is a "macro" government policy, outside the control of NASA (and manipulable only within severe limits by the Federal Reserve Board). The second option, reducing the private-sector R&D costs by having the government fund some of it, is much more localized. It can be implemented by an independent agency like NASA with little impact on other policies.

Table 5-6 also suggests that for a given total investment, returns are higher the more quickly they are achieved (the benefits are reduced less through discounting). This effect is much stronger for the public sector than for the private. This is true because the government spends its R&D money up front, but realizes its benefits only after the private sector has implemented the actual program. Thus, long R&D programs severely penalize the government return. There are many obvious reasons why the shortest possible

Table 5-6. Internal Rates of Return as Function of Total Required R&T Investment and Spending Rate--STOL Case

	Duration	Rate	Public IRR*	Private IRR**
If a total of $100M in R&T is required:				
	2	$50m/yr	29.2%	9.9%
	5	$20m/yr	25.5%	9.6%
	10	$10m/yr	20.7%	9.1%
If a total of $500M in R&T is required:				
	2	$250m/yr	14.3%	4.8%
	5	$100m/yr	12.7%	4.5%
	10	$50m/yr	10.6%	4.0%
If a total of $1000M in R&T is required:				
	2	$500m/yr	11.3%	1.3%
	5	$200m/yr	7.6%	1.1%
	10	$100m/yr	6.4%	–

* Counts value of time savings only

** If private sector must pay product plus R&D costs program is not, in fact, optimum,[206] but it is interesting to see that the pressures for short-term government programs introduced in Chapter 1 are more than merely political, they also have an economic underpinning.

Comparing the public-sector rates of return in Table 5-6 to the those of the private sector, we also see that the public sector's IRR is much less sensitive to delays than the private sector's. Thus, not only are the absolute incentives lower, the penalties for waiting are lower. This reinforces the conclusion in Chapter 4 that the private sector will underinvest in R&D.

We can now summarize the "starting tests" suggested in the figures above:

- The private sector should have a long-term prospect for achieving financial return;
- The private sector's short-term incentives should be low due to the cost or time of the R&D investment required;
- Public-sector benefits should exist that are not accounted for in private calculations, and should be large enough to justify the proposed public investment.

If these criteria are met, then the government should examine the possibility of constructing a joint program whereby the R&D costs are shared.

Both examples treated in this chapter illustrate how external conditions can change the incentives even if the research itself is successful. The dangers of running "open-loop" suggest that some comparable stopping test is desirable. Such a test would be applied periodically through the life of a research program (probably as part of the annual budget cycle). The logic of the starting test described above can be expanded, with two major cases needing consideration.

The first case would occur when the private sector curve moves into the feasible region. This would imply that the NPV as evaluated by a private company had become positive, and would be a strong indication that the government's research program could be concluded or redirected. This was, of course, the goal in the STOL case, and it apparently is being achieved in the case of the ATP. Such results should be viewed as policy successes.

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206 For example, rapid changes in R&D programs are disruptive and generally inefficient.

The second case would occur when the government curve moved entirely into the infeasible region, so that it was no longer considered likely that the government would realize positive gains from the research program's primary results. This could occur either because the technology was not developing as planned, or because of changes in the operating environment, or because of some combination of the two. This is in fact what occurred in the STOL example. The technology was developing adequately, but the projected traffic growth did not. By 1973 the case for STOL had weakened, and by 1976 the launch of a major STOL research program would no longer have appeared to be justified, based solely on civil considerations.

These conclusions suggest that there is an optimum funding level for government investment in these types of projects (see Figure 5-18). Below some threshold, the uncertainties are not sufficiently reduced to stimulate private sector investment. Once the private sector's development is launched, public returns rise very rapidly. Further government funding may increase the public returns slightly, but it will eventually lead to a drop in returns since benefits are being diluted unnecessarily. It is impossible to have *a priori* knowledge of what this curve looks like for a given program, but the step increment can almost certainly be recognized when it occurs. Thus recognition of this effect is important to the R&D planning process.

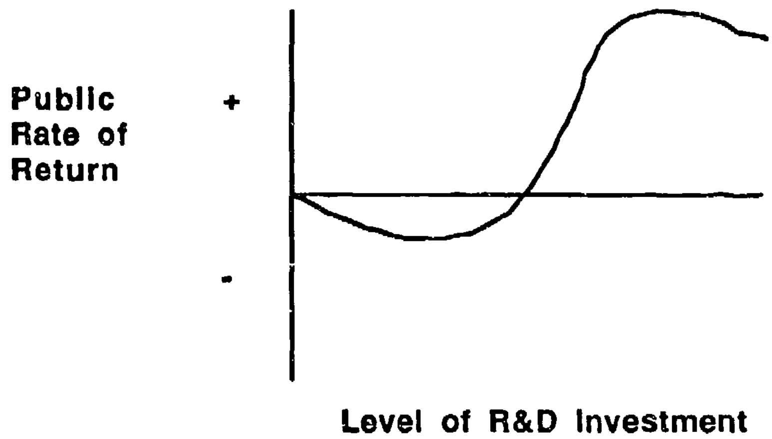

Figure 5-18. Public investment in R&D that accomplishes public goals through private spending can be expected to exhibit a step function in terms of public returns. Below some threshold, uncertainty is insufficiently reduced to stimulate private spending. Once the private program is launched, however, public returns rise rapidly.

CHAPTER 6. R&D FOR REGULATION

Economic incentives do not always drive public and private-sector decisionmaking in common directions. As discussed in Chapter 1, regulation is sometimes used as a policy tool to correct situations where the market does not properly reflect the true social costs or benefits of an activity. Government regulation in aeronautics may be divided broadly into four categories:

-- Economic regulation;

-- Health and safety of participants;

-- Health and safety of non-participants;

-- Protection of the natural environment.

This chapter focuses on the third category, and specifically, the issue of aircraft noise reduction. The issues, and hopefully the lessons, apply to all four categories. How does R&D influence regulation, and how does regulation affect the incentives for or direction of R&D? The general argument is that R&D and regulation are complementary strategies, in that the former changes the possibilities within which the latter occurs. Properly coordinated, government R&D can provide "technology push" and regulation the "market pull," a combination that has historically led to rapid technological diffusion.

The lessons of the aircraft noise example do not invalidate this general model, but they do make emphatically clear that such complementary roles cannot merely be assumed. The case study in Chapter 3 shows that NASA conducted an aggressive technology demonstration program that showed significant noise reductions were possible. This chapter analyzes how the NASA results were used by the FAA to conclude that noise reduction had severe economic penalties. I will argue that the FAA promulgated regulations which, in retrospect, had a small impact on the noise situation relative to what could have been achieved with full exploitation of the NASA results. I conclude that the economic penalties suggested by the FAA's cost-benefit analyses were largely due to the mismatching between engine size and airframe needs, rather than to noise reduction features *per se*. Finally, the rapid rise in fuel prices that actually occurred during the latter half of the 1970s suggests that an aggressive retrofitting program *with properly sized engines* would have had a positive, rather than negative, economic impact on the airlines.

These conclusions raise important questions about the legitimacy of constraining the NASA role to "technology demonstration" if indeed it is to be depended upon as the national source of public-interest aviation technology, as it was in the aircraft noise case. The sections that follow begin with an examination of the politics of noise reduction, which provides the context in which decisions were actually made. Next, the cost-benefit analyses used to guide the regulatory decisions are reviewed. The actual net result of the noise regulation program is examined in the third section. The final sections analyze alternative courses of action and reexamine the cost-benefit analyses in light of developments that have actually occurred.

6.1 THE POLITICS OF AIRCRAFT NOISE REDUCTION

The elements of the NASA noise reduction program were presented in Chapter 3. Before examining the impact and effectiveness of the program, however, it is instructive to review briefly the politically charged environment in which the decisions were made. In addition to the manufacturers, the airlines, and the FAA, NASA's program interacted with Congress, the Courts, state and local governments, and the EPA. To understand how NASA's policy evolved, we must ask how each of these groups viewed, and used, R&D.

The Courts. For much of American history, a phenomenon like aircraft noise might simply have been dismissed as a "cost of progress."[207] By the middle of the twentieth century this doctrine had been largely abandoned. The legal system provided a relatively rapid and accessible means for the public expression of concern over the issue of aircraft noise.

The three primary bases for grievances about aircraft noise have been *trespass* (the peaceable but wrongful entry upon another person's land), *nuisance* (interference with another's use or enjoyment of property), and *inverse condemnation* (the taking of private

[207] In many railroad cases, for examples, nuisances caused by legal activities were not recoverable takings. See Lexington Ohio Railroad vs Applegate or Richards vs Washington Terminal Company (233 U.S. 546).

property by a governmental entity without prior compensation).[208] Of these, inverse condemnation has been by far the most sustained and defensible approach.[209]

Three Supreme Court cases have been particularly influential in guiding the noise reduction issue. In the 1946 case United States vs Causby (328 U.S. 256), the Supreme Court rejected the argument of trespass but ruled that the government, through low flights of military aircraft landing adjacent to the Causby chicken farm, made the property unusable and constituted a "taking" in the constitutional sense. The 1962 case, Griggs vs Allegheny County (369 U.S. 84, 1962) extended this and established that airport owners and operators, rather than aircraft builders, owners, or pilots, were the parties liable for damages due to aircraft noise. The Court ruled that airport authorities were responsible for design and siting, and thus for acquiring enough property around the airport so as not to constitute a later taking from nearby individuals. In City of Burbank vs Lockheed Air Terminal, Inc (411 U.S. 624, 1973) the Court overturned local ordinances constraining activities of a privately owned airport, primarily on the grounds that the Federal government had, through various mechanisms, so totally preempted the field of commercial aircraft regulation that there was no room for local regulation. These cases have lead to the current situation, where airport owners and operators are free to set the timing of operations and level of allowable noise as long as they are (1) nondiscriminatory in the application of these laws and (2) do not actually affect the flight paths of specific aircraft.

Most airports are owned by state or local organizations, so the legal precedents have created the paradoxical situation that while local governments cannot constrain a privately held airport, they can restrict hours of operation at their own facilities, in effect, making local trades between the value of commerce and the cost of noise. Recently this has led to elaborate procedures for allocating airport access based on aircraft noise (especially at the John Wayne Airport in Orange Country, California). The uneasy situation continues, with the problem clearly unsolved by the legal system.

Congress. In September 1959 the House Committee on Interstate and Foreign Commerce held their first public hearings. In 1960 the House Committee on Science and

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[208] See Elizabeth Cuadra, "Aircraft/Airport Noise and the Courts," Chapter 38 of Cyril M. Harris, *Handbook of Noise Control*, 2nd Edition, (McGraw-Hill, 1979).

[209] Following the introduction of commercial jets a variety of attempts were made to enjoin aircraft operation by one legal means or another. In Allegheny Airlines, Inc. vs Village of Cedarhurst (238 F. 2d 812, 1956) a local town sought to prohibit aircraft from passing below a specified altitude. In American Airlines vs Town of Hempstead (272 F.Supp 226, 1967) the town sought to prohibit the emission of specific levels of noise.

Astronautics commissioned a special study, followed in 1963 by a study from the Commerce Committee. Both studies attempted to portray aircraft noise as a scientific, rather than legislative, problem. Throughout the 1960s NASA received a continuing flow of inquiries from various Congressmen about what it was doing to reduce aircraft noise.[210] Largely in response to Congressional pressure, OST convened its aircraft noise group in October 1965.[211] Congressional interest continued with special hearings in 1967, 1968, 1972, 1973, 1974, 1975, and 1977. The Committees with direct responsibility for NASA tended to view aircraft noise as a technical problem that NASA should play a major role in solving. (In 1965, for example, the House Space Subcommittee ordered NASA to increase it noise-related spending from $485,000 to over $2.4 million.)[212] Committees with responsibility for transportation in general tended to see aircraft noise as more of a local problem, with an emphasis on administrative solutions.

FAA. With the passage of PL90-411 in 1968, Congress formally chartered the FAA to promulgate regulations on aircraft noise. Treating noise as another aspect of airworthiness requiring Federal certification, the FAA created Part 36 of the Federal Air Regulations in 1969 (FAA rulemaking actions relating to aircraft noise are summarized in Table 6-1). Under the 1969 rules, all new transport types were required to meet specific noise limits at defined takeoff, sideline, and approach measuring stations. Existing aircraft types were excluded until 1974, when the rules were extended to include all new production aircraft. Finally, in 1977, the standards were tightened and time limits were set for older aircraft that did not meet the original standards.[213] Under FAR-36 as presently constituted, "Stage I" aircraft are those which do not meet FAR-36 standards, and all of these were removed from service by 1985 or are operating on special waivers. "Stage II" aircraft are those that meet the original 1969 requirements. Since 1977 all new types of aircraft must meet tightened "Stage III" requirements, but there is currently no cutoff date for the operation of existing Stage II aircraft.

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210 See *NASA Aircraft Noise Research, Chronology of Related Events 1962-1965*. Unsigned, undated memo in OART files.

211 Rep. Herbert Tenzer of New York claimed responsibility for the OST study (123d, *Aircraft Noise Control*, page 14) and this is corroborated by the NASA files.

212 The amount was eventually reduced to $1.4 million, but it sent the Headquarters staff reeling. See House Report #1240, p. 59, plus internal NASA memos May 12, 1964 and November 13, 1964.

213 FAR Part 36, Amendment 7 (42 Fed. Reg 12360), March 3, 1977. Under FAR Part 91, Amendment 136, phased compliance with FAR Part 36 was implemented requiring all aircraft operating in the U.S. to meet Stage II standards by January 1, 1985.

Table 6-1. Summary of FAA Rulemaking Actions on Aircraft Noise

Date	Number	Title
12/1/69	**FAR-36**	**Noise Standards: Aircraft Type Certification**
10/30/70	ANPRM 70-44	Civil Airplane Noise Reduction Retrofit Requirements
9/13/71	NPRM-71-26	Noise Type Certification and Acoustical Change Approvals
1/24/73	ANPRM 73-3	Civil Airplane Fleet Noise Requirements
8/4/70	ANPRM 70-33	Civil Supersonic Aircraft Noise Type Certification Standards
4/27/73	**FAR-91.55**	**Civil Aircraft Sonic Boom**
7/7/72	NPRM 72-19	Newly Produced A/C of Older Type Design:App of Noise Standards
12/1/73	**FAR-36 A-2**	**Extension of FAR-36 to New Production Aircraft**
1/20/75	FAR-36 A-3	Acoustic Change
2/7/75	FAR-36 A-4	Small Propeller
9/20/76	FAR-36 A-5	Test and Data Correction
1/24/77	FAR-36 A-6	Test Procedures
1/28/77	FAR-91 A-134	Reduced Flap
10/1/77	**FAR-36 A-7**	**Stage III Noise Level Limits**

A flow chart of the FAA rulemaking process (Figure 6-1) suggests its complexity.[214] Although consideration of R&D does not explicitly appear in this process, it occurs informally at many points. Interaction between NASA and the FAA has been extensive but sporadic. Prior to 1965, consultation on aircraft noise reduction was largely informal. Formal coordination began in October, 1965, when the President's Science Advisor convened an interagency panel of experts to assess the aircraft noise problem. The report of this Ad Hoc Jet Aircraft Noise Panel became the blueprint for an interagency drive to reduce aircraft noise. The Interagency Aircraft Noise Abatement Program (IANAP), announced by President Johnson in a speech to Congress in March, 1966 brought together all the relevant Federal agencies for a concerted attack on aircraft noise. OST chaired the effort until the Department of Transportation was created in 1968 and authority for the IANAP passed to the FAA. The FAA established a joint noise office and operated it until the creation of the Environmental Protection Agency (EPA).

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214 Charles D. Foster and R.W. Danforth, "Regulation of Aircraft Noise," in *Handbook of Noise Control.*

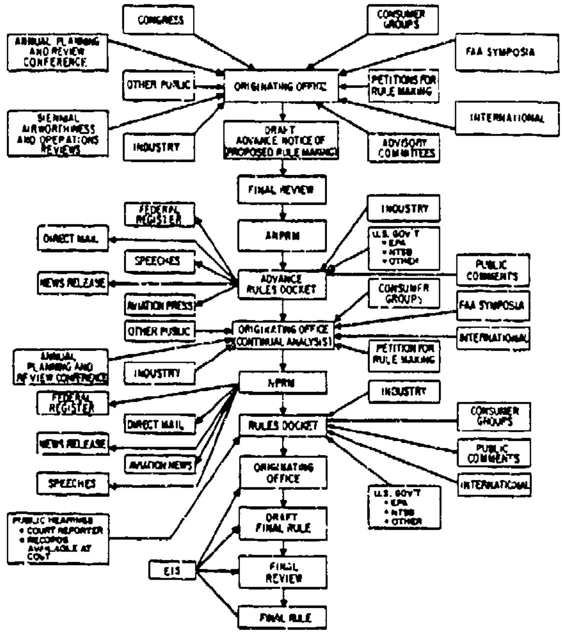

Figure 6-1. Flowchart of the FAA Rulemaking process.
Source: Charles D. Foster and R.W. Danforth, "Regulation of Aircraft Noise," in *Handbook of Noise Control.*

The Environmental Protection Agency. In 1970 Congress passed the Clean Air Act (PL91-604) which assigned to the newly-created Environmental Protection Agency the task of studying the noise problem and determining its impact on public health. The resulting EPA report[215] led to the Noise Control Act of 1972 (PL92-574). The primary impact of the Act on aircraft noise was to mandate an EPA study on the adequacy of the FAA regulations, and to amend the FAA charter giving the EPA a vague authority to propose new noise regulations upon which the FAA was required to act, but not to necessarily adopt (see Figure 6-2). Significantly, Congress did not change the wording of the FAA charter that proposed standards be both "economically reasonable" and "technologically practicable."

[215] Environmental Protection Agency, *Report to the President and Congress on Noise.* Government Printing Office, Senate Document 92-63, February 1972.

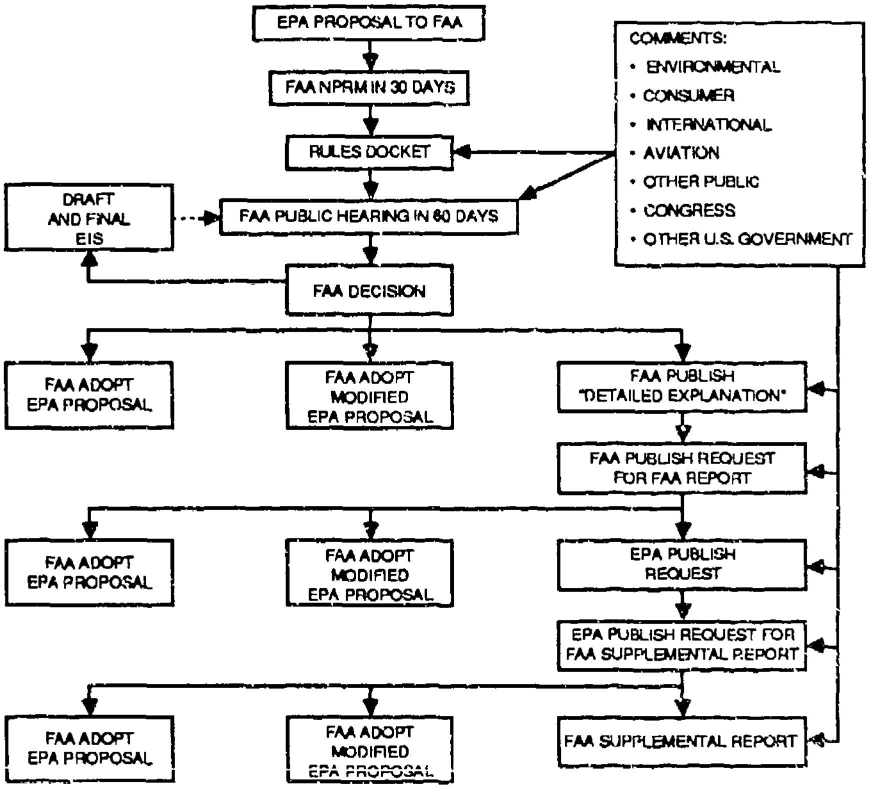

Figure 6-2. Rulemaking process for EPA/FAA coordination as required under the Noise Control Act of 1972.
Source: Charles D. Foster and R.W. Danforth, "Regulation of Aircraft Noise," in *Handbook of Noise Control.*

In 1973 the EPA issued a study of the FAA's noise regulations that was strongly critical of the FAA but stopped short of making specific national targets for "acceptable" noise levels around airports.[216] The primary finding by the EPA was that neither the FAA's flight and operational controls nor their aircraft noise emission standards "adequately protect the public health and welfare from aircraft noise." The primary criticism of the FAA operational procedures was that there were no standardized flight procedures for minimizing noise and especially that the two-segment approach had not been implemented. The criticism of the FAA's noise emission standards was that they were being implemented too slowly; the EPA generally approved the concept of a Fleet Noise Rule and the extension of FAR-36 to all aircraft, rather than just new production.

[216] Environmental Protection Agency, *Report on Aircraft-Airport Noise*, Government Printing Office. Serial Number 93-8, August 1973.

After all its investigation, however, the EPA was unable to identify any specific level that would adequately protect the public health and welfare. The EPA proposed its own measurement standard, the day-night average noise level (L_{dn}), and calculated the costs of achieving a range of L_{dn} levels around airports. The EPA cautioned, however, that even the identification of an "acceptable" overall noise exposure level might expose the Federal government to liability:

> Separate legal implications are associated with "identifying" and with "achieving" levels of cumulative noise adequate to protect the public health and welfare from aircraft/airport noise: (1) Identification of cumulative noise levels at particular airports to protect the public health and welfare could be used to support additional litigation against airport owners. This could follow from the mere act of "identification;" (2) Under the Burbank decision, overall Federal regulation is necessary; (3) Federal regulation, including Federal airport noise certification, may shift liability from airport owners to the Federal government; but "achievement" should reduce airport noise liability. There are also possible liabilities for the Federal government as the proprietor of military airports; (4) Any shift in liability to the Federal government may be a problem during the period between Federal identification and the achievement of noise levels requisite to protect the public health and welfare. If the court were to hold that liability had shifted by reason of preemption, a legislative solution for the interim period is unlikely because liability would probably be based on the constitutional requirement that just compensation must be paid for the taking of property."[217]

Since the EPA's cost estimates ran as high as $33 billion, and since any finding of a safe level around airports might logically be extended to other areas of society, the EPA was reluctant to set up expensive regulations that it could not not justify on an objective scientific basis. Since the primary complaint was still annoyance, that basis proved very difficult to establish.

The EPA's role in aircraft noise reduction has been strongly criticized, particularly its role in coordinating R&D. In 1977 the General Accounting Office concluded that "the EPA has not been effective in promoting the coordination of Federal noise research and control efforts."[218] After the EPA assumed responsibility for the activities of IANAP, the group met only once and published but one report.

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[217] *Report on Aircraft-Airport Noise*, pp. 112-113.

[218] General Accounting Office, *Noise Pollution--Federal Program To Control It Has Been Slow and Ineffective*, CED-77-42, March 7, 1977.

Relations between the FAA and EPA were frequently strained. NASA staffers apparently enjoyed good relations with the EPA, even as the level of activity was declining. The EPA relied heavily on NASA for technical advice.

Summary. When all of these interactions are considered, it appears that in addition to whatever technical contributions it actually made, NASA's aircraft noise research had five major political roles:

The hope of a technical fix. NASA became involved in noise research because of direct Congressional pressure. This pressure was generated first and foremost by the perception that aircraft noise was primarily a technical problem, and that, therefore, it should have a technical solution. NASA's technical prowess was highly regarded, and it is clear that many in Congress hoped that NASA could provide a quick fix to the noise problem and thus prevent controversial political choices.

A symbol of the government's concern. Once it became clear that a quick, inexpensive technical fix was not going to occur, NASA research became important as a symbol of the government's concern for citizens affected by the problem. With research hardware, NASA was the one place in government legislators could point to tangible progress. Much of the noise problem resulted from the prospect that things were going to get worse; NASA research held out the counterhope that things would get better.

A source of objective data. Assessing the damage from noise exposure, determining reasonable standards for regulation, and estimating the cost of implementation all required reliable data, and NASA was in the best position to provide it. Unencumbered by regulatory or operational responsibilities, and without economic interests, NASA was virtually the only institution in the government that had both the expertise and the capability to quickly undertake noise research. All of the major sectors appeared to accept NASA's data. One of the major products of NASA's demonstration programs (Acoustic Nacelle, Quiet Engine, REFAN) was a set of cost/effectiveness points accurately quantifying the reduction in decibels versus the cost of various options.

Increased efficiency in the nation's technical effort. NASA research did not relieve private industry of its burden to conduct noise reduction R&D (since most of the costs are incurred in development), but rather, it provided leverage to private spending. In addition to hosting government/industry conferences and publishing the results of its own research, NASA went to unusual lengths to promote the rapid dissemination of basic knowledge. One of the key provisions in NASA's early noise contracts was that participating companies were required to open their internal files to NASA, and to publish in the open literature everything NASA determined to be of relevance.

A sign of good faith to industry. The government had actively promoted the development of the air transportation industry, and was genuinely concerned that the noise problem not be allowed to cripple what had become an important national asset. All of the noise reduction programs considered imposed direct monetary costs on the airports, airlines, and manufacturers, who were quick to use these costs as political arguments against regulation. Assisting the private sector by funding the research was one means of defusing criticism of the regulations.

6.2 REGULATORY OPTIONS AND COST-BENEFIT ANALYSIS

The economic arguments for government environmental regulation are fairly well established. To residents living near airports, noise has many disbenefits, ranging from annoyance to loss of sleep to a decrease in property values. To the airlines, however, noise is an externality in the sense that in an unregulated market there is no cost associated with its production. In such a situation, one expects that more noise will be produced than is economically efficient or socially optimum.

In theory, an economically efficient solution could be reached by quantifying the various costs of noise (psychic, litigation, property devaluation, and physical damage) as a function of noise exposure and comparing them with the costs of noise control (changes in operation, engine or airframe modifications, weight of sound-absorbing material, or direct land purchase). The marginal costs of each could be compared and regulations designed that would implement a solution where the marginal costs were equal.

In practice, of course, this is extraordinarily difficult and direct solutions such as transfer payments are rarely implemented. Aside from the obvious problems of actually measuring many of these social costs of noise, there are questions of equity, in terms of how they should be distributed. Instead, more centralized approaches are typically undertaken, with the government acting as broker and the affected parties never directly confronting one another. This occurred in the aircraft noise case and is best illustrated by two studies that used systems analysis and cost-benefit analysis in attempting to resolve societal disputes. The first study was conducted by the National Research Council, the second by the FAA.

Late in 1969, the Port of New York Authority (PONYA) was considering expansion of John F. Kennedy International Airport. Their primary option was to construct new runways by filling in a significant portion of adjoining Jamaica Bay. Although these new runways would then have significantly less noise impact on the surrounding community than other alternatives, the potential for ecologic damage to the wildlife refuge in the bay was severe. PONYA requested the National Academy of Sciences (NAS) to conduct an environmental impact study on the problem and alternative solutions. The idea received strong support from both the Departments of Transportation and Interior, who saw it as an opportunity for an important pilot program that would not only benefit New York but also serve as a model for other communities. A joint study group was appointed from the ranks of the NAS and the National Academy of Engineering.

The study is important because a diverse, highly educated interdisciplinary group studied the noise problem in its full "systems" context, and recommended a strong technology push while criticizing the existing basis for noise regulation. The group concluded that any runway construction would indeed damage the ecology of the area, and suggested that it would be better to seek solutions to the Kennedy Airport problem through "technological means." Among the suggestions were: improved air traffic control (to increase the effective capacity of existing runways), access control through variable landing fees (to distribute the distribution of noise and to cut down on general aviation traffic), building another airport for New York, enforcing strict building codes for noise insulation on surrounding communities, and finally, a major effort to promote quiet aircraft.

Citing the results of NASA's Acoustic Nacelle and Quiet Engine programs, the report urged all relevant agencies to press for the development and installation of quiet engines on aircraft; with mandatory acoustic nacelle treatment and a 10 EPNdB tightening of FAR-36 regulations by 1975. While acknowledging that progress had been made with the latest generation of new airliners, the panel viewed the advances largely as "a happy coincidence between the requirements for improved aircraft performance and the requirements for noise reduction."[219] They noted that no compromises had been made in performance to reduce noise, and cited the NASA results as evidence of what could be obtained if compromises were accepted. "Our thesis here is that aircraft and engine design

[219] National Academy of Sciences and National Academy of Engineering, *Jamaica Bay and Kennedy Airport: A Multidisciplinary Environmental Study*, National Academy Press, 1971.

should and in fact must be compromised by noise considerations in the future--by a rational tradeoff between performance and community noise impact."[220]

At the same time it urged the tightening of standards, the study questioned whether the approach used in FAR-36 (regulation of individual aircraft) was an appropriate long-term solution. Total community exposure as measured through NEF was what counted most, they argued, and any scheme to regulate only individual aircraft types would not limit noise impact due to increases in traffic. Not only that, but restrictions on aircraft type might actually send the wrong signals to the manufacturers and the airlines. The study noted that on a per-passenger basis, NEF exposure was essentially independent of aircraft weight, while EPNdB scales linearly with gross weight. Thus, a regulation based on fixed EPNdB limits (such as the PONYA 112-dB limit and FAR-36 above 600,000 lb) discriminated against large aircraft and allowed small ones to be unnecessarily loud. Since small aircraft need a larger number of flights to carry a given number of passengers, fixed EPNdB limits could actually increase overall NEF. The study recommended that regulation be based on acceptable overall community noise exposure, with airlines allowed to trade size and frequency as needed to stay within the limit.

The approach recommended by the NAS for Jamaica Bay was not adopted nationally. Instead, the FAA relied on cost-benefit studies that concluded minimum retrofitting with SAM was the most effective alternative.[221] The FAA examined five major alternatives, including (1) retrofitting all JT-3D and or JT-8D powered aircraft with new nacelles containing Sound Absorbing Material (SAM); (2) retrofit of all JT-8D powered aircraft with refanned engines, (3) adopting 2-segment approach procedures, (4) modifying takeoff procedures; and (5) acquisition of all land within specific noise contours. Costs were estimated as costs to airlines or cost of purchasing land. The benefits were estimated entirely by the increase in property values due to decreases in noise levels. The results are summarized in Table 6-2.

Largely on this basis, the FAA elected not to promulgate regulations during the 1970s that would require extensive retrofitting. In 1974 the FAA required all newly produced transport aircraft to comply with FAR-36, but not until 1985 was compliance for

220 *Jamaica Bay and Kennedy Airport*, p. 114.

221 C.R. Foster, *Retrofit on non-noise certified subsonic jet aeroplanes*, ICAO Working Paper CAN/4-WP/56, February, 1975.

Table 6-2. Costs and Effectiveness Options Considered by FAA

Option	Available[1]	Cost[2]	Benefit	% Population[3]	Ratio
T/O Cutback	1978	–	932	25	∞
T/O & 2-seg appch	1978	75	2797	33	37
SAM 3D/8D + T/O CB + 2 seg	1978	1042	5594	53	5.3
SAM 8D	1978	320	932	12	2.9
SAM 3D/8D	1981	967	1864	21	1.9
SAM 3D/Refan 8D T/O + 2 seg	1981	5072	7065	55	1.4
REFAN 8D/SAM 3D	1981	5001	4416	47	0.9

Source: C.R. Foster, *Retrofit on Non-Noise-Certificated Subsonic Jet Aeroplanes.*

Notes:
1. Year that implementation would be completed w/1975 go-ahead.
2. Cost & benefits in millions of FY75 dollars.
3. Percentage of 6.2 million residents that would be removed from NEF 30+ exposure.

all operational aircraft mandatory. Under Amendment 7 to FAR 36 (42 Fed. Reg. 12360) new aircraft types certified after 1977 were required to meet stricter noise requirements, but at the time of this writing no requirement had been enacted that would require compliance with these "Stage III" limits by all operational aircraft.

6.3 RESULTS OF THE NATIONAL NOISE REDUCTION EFFORT

What has actually been achieved in terms of aircraft noise reduction? The answer for individual aircraft types is clearly shown in Figure 6-3. A steady downward trend has been achieved for each new type certified. But several previous sections have noted that what really counts is the cumulative national exposure of people to noise, not the noise produced by a given individual aircraft. Although both the EPA and the FAA have produced projections of total noise exposure,[222] I have been unable to find any study or analysis that tracks the historical noise exposure over time on a national basis. The remainder of this section presents a first cut at such an analysis.

[222] The EPA document *Noise Exposure of Civil Aircarrier Airplanes Through the Year 2000* (EPA 550/9-79-313-1, February 1979) for example, contains detailed projections, but no historical records.

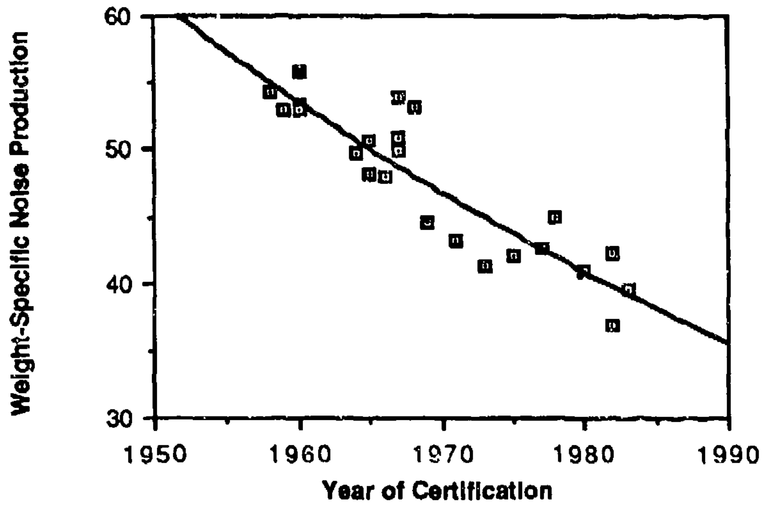

Figure 6-3. Noise levels of commercial transport aircraft plotted against year of introduction into commercial service. Values shown are weight-specific noise production, defined as the average of all three FAR-36 stations normalized for one pound of takeoff weight.

Perhaps the most relevant measure would be a historical record of actual noise exposure, using the Noise Exposure Forecast methodology discussed on p. 72. The effort required for this calculation would probably be equal to that for an entire thesis; however, a first order calculation can show the important trends. Any such calculation must include some measure of: (1) source noise, (2) population or area exposed, and (3) traffic volume. As a first cut, we can calculate the total land area exposed to a given noise level in a given year, N_t:

$$N_t = \Sigma A_i \, n_{i,t} \quad \text{(for all i)}$$

where i is the aircraft type, t is the year, A_i is the area (square miles) exposed to a given noise level or higher per operation, and $n_{i,t}$ is the number of operations of type i in year t. Clearly, such a method has serious shortcomings, most notably that: (1) it does not account for the land use of the area exposed, and thus, provides only a secondary measure of the population exposed (takeoffs over water, for example, count the same as flights over downtown); (2) it does not account for time of day of the overflight; and (3) it assumes that the effect of multiple overflights is linear, with no thresholds. The primary advantage of the method is that it is simple and uses data that are readily available. Total noise exposure is plotted in Figure 6-4.

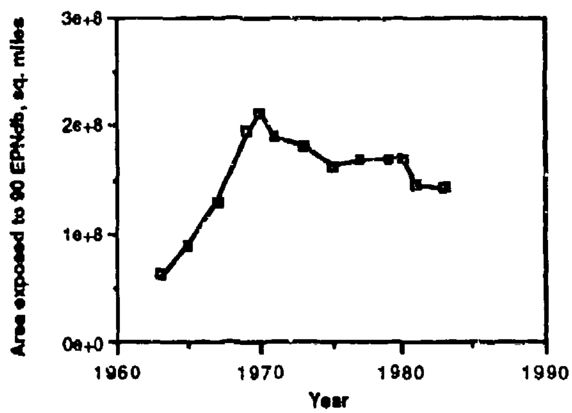

Figure 6-4. Total annual area (in square miles) exposed to 90 EPNdB or greater due to aircraft operations. This graph was prepared by multiplying the total number of operations per year for each aircraft type (available from FAA records) by the total area exposed per operation (Table 6-3).

This calculation suggests that the total national noise exposure peaked in the early 1970s and had declined by about a third by 1980, primarily due to the phase-out of the B-707 and DC-8 aircraft. It is interesting to note that the absolute exposure in 1980 was still about 30 percent higher than in 1965, a time when the noise problem was judged to reach crisis proportions. Since aircraft noise is no longer perceived to be an urgent national problem, this suggests that the perceived derivative is more important for public policy than the absolute magnitude of the problem.[223]

Figure 6-4 also points up the importance of technological diffusion. The development of new, quiet technology accounts for little if it is not disseminated into the fleet; given a slow diffusion of the new technology, the overall traffic level is a more important determinant of total noise exposure than development of new, quiet technology. Few anticipated that designs would last as long as they have. Developing the technology for quiet aircraft proved relatively straightforward compared to getting it into the fleet.

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223 An alternative explanation, suggested by Ivan Oelrich of IDA, is that over a fifteen-year period noise-intolerant people moved away from airports--in effect, the market moved noise-tolerant people or activities into high-noise areas.

Table 6-3. Noise Levels of Common Turbofan-Powered Commercial Aircraft

				FAR-36 Levels (EPNdB)					
Type	Year[1]	Stage[2]	GTOW[3]	Thrust[4]	T/O	Side	App	WSNP[5]	Area/Op[6]
B-707-100	1958	1	258	72	107	102	116	54.2	99
DC-8	1959	1	315	68	105	107	112	53.0	120
B-707-320	1960	1	336	76	112	103	118	55.7	156
B-720	1960	1	235	72	104	103	114	53.3	74
CV-880/990	1960	1	325	88	105	107	112	52.9	102
B-727-100	1964	1	170	44	97	99	110	49.7	31
BAC-111	1965	1	100	24	96	102	104	50.7	30
DC-9-10	1965	1	90	29	92	98	103	48.1	11
B-727-100QC	1966	2	161	44	97	99	104	47.9	16
B-727-200	1967	2	191	47	101	100	110	50.9	35
DC-8-6x	1967	1	325	68	110	103	114	53.9	85
DC-9-20-50	1967	1	120	31	96	102	104	49.9	28
B-737	1968	2	111	29	104	104	103	53.2	41
B-747	1969	2	750	182	106	98	106	44.6	18
DC-10-1x	1971	2	440	125	97	97	105	43.2	13
L-1011	1973	3	430	126	96	95	102	41.3	7
DC-10-4/5	1975	3	570	162	97	97	105	42.1	13
A-300	1977	3	325	102	96	95	102	42.5	7
B-747SP	1978	3	700	182	106	98	106	44.9	17
MD-80	1980	3	140	42	90	94	93	40.9	4
B-757	1982	3	220	77	93	94	100	42.2	5
B-767	1982	3	300	96	93	95	87	36.9	4
DC-8-7x	1983	3	350	88	94	93	98	39.6	4

Notes:
1. Year of introduction to U.S. commercial service.
2. Certification stage under FAR-36.
3. Gross Take-off Weight, in thousands of pounds.
4. Maximum installed thrust, thousands of pounds.
5. Weight specific noise production: = EPNdB – 10 log (weight in lbs); essentially, noise level normalized to 1 lb of GTOW.
6. Area in square miles exposed to 90 EPNdB noise level per operation (takeoff + landing. author's calculations).

How much of the decline is attributable to regulation, and how much is merely happy coincidence due to the introduction of high-bypass-ratio engines? A rough estimate can be made by comparing the noise of the C-5A military transport with that of the commercial B-747. The C-5A had severe range requirements that placed an absolute premium on specific fuel consumption. This led to the selection of a high bypass ratio (8) on the TF-39 engine, and essentially no regard for noise production. The 747, on the other hand, was the first aircraft required to meet FAR-36. The initial versions could not in fact meet the regulations and required special waivers, but later versions did. Table 6-4 compares the C-5 and the two versions of the 747 on the basis of weight-specific noise production, or WSNP. Using this measure, the C-5 and the early 747s appear to have essentially the same level of noise technology, about 52 EPNdB/lb. FAR-36 required a real and significant reduction of about 7 EPNdB on the 747. Thus, when compared to first-generation low-bypass-ratio turbofans (which had WSNP levels of about 52, see Table 6-3) most of the noise reduction on the 747-class appears to have come as result of intentional noise reduction engineering rather than from the adoption of high-bypass-ratio engines *per se*.

Table 6-4. Estimating the Impact of Noise Regulations on Specific Noise Production

Type	GTOW	Take-off	Sideline	Approach	Ave WSNP
B-707-320	336	112 (56.7)	103 (47.7)	118 (62.7)	55.7
B-727-200	191	101 (48.2)	100 (47.2)	110 (57.2)	50.9
C-5A	800	117 (58.0)	106 (47.0)	113 (54.0)	53.0
B-747-100 early	720	115 (56.4)	103 (44.4)	114 (55.4)	52.1
B-747-100 certified	720	107 (48.5)	98 (39.4)	107 (48.4)	45.5

( ) = WSNP

Sources: C-5A: AD-A053-700. B747: AIAA-73-1157.

This information allows us to estimate what might have happened in the absence of Federal noise regulations. Figure 6-5 shows the total noise exposure that could have been expected if (1) all low-bypass-ratio jets retained their original levels; (2) all high-bypass-ratio jets had WSNP levels of 50, and (3) traffic level and fleet mix had remained unchanged.[224] The absolute noise exposure would have continued to rise, albeit at a much slower rate, until the end of the 1970s.

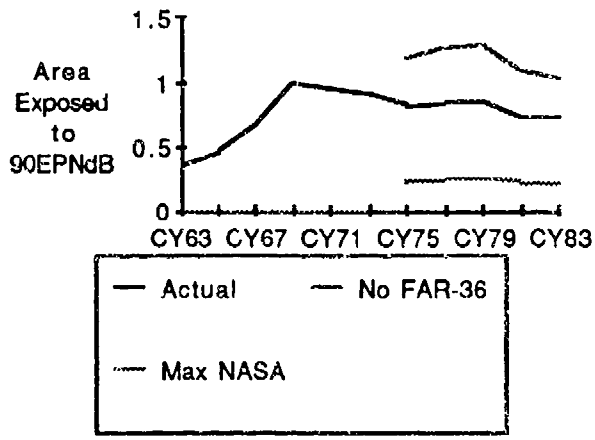

Figure 6-5. Noise exposure versus time for two hypothetical cases. The top curve represents the likely noise exposure had no government regulation taken place at all. The lower curve illustrates the maximum reduction that might have been achieved if regulatory standards reflected demonstrated technology levels rather than commercially available hardware. The reference level is 1970, an annual exposure of 200 million square miles at 90 EPNdB or greater (see Figure 6-4).

A second hypothetical case worth examining is what would have occurred if NASA's noise-reduction technology had been fully utilized. The Quiet Engine aimed at 89 EPNdB for a DC-8 at takeoff, which translates to a WSNP of about 34. The QCSEE engine pushed even farther, with a sideline noise goal of 82 EPNdB on a 150,000 pound aircraft, requiring a WSNP of about 30. These numbers proved to be achievable on research engines, suggesting that a WSNP of 35 would certainly be technologically achievable in practice. Applying a WSNP of 40 to all aircraft fitted with low-bypass-ratio engines (achievable either with a retrofit to high-bypass engines or with acoustic nacelles) and a WSNP of 35 to all new aircraft produces a third curve, which is labeled "max NASA," or maximum application of NASA technology.

224 This latter assumption is certainly arguable, especially for the late 1970s and early 1980s when most airlines phased out their B-707 and DC-8s, but how much of this reduction was scheduled retirement, how much was economic due to the increased fuel costs, and how much was needed to meet noise requirements is impossible to gauge.

Figure 6-5 can be interpreted as both a success and a failure for the government's noise-reduction program. The program appears to have been successful in capping the nation's total noise exposure (the peak appears to have come in 1970, only one year after FAR-36 was promulgated). In the absence of FAR-36, total noise exposure would have continued a gradual increase for almost another decade, eventually increasing by about 30 percent before beginning to decline early in the 1980s. On the other hand, Figure 6-5 clearly illustrates the tremendous missed opportunity. Under FAR-36, absolute noise exposure has declined about 30 percent from its actual peak. It could have declined by 70-80 percent had NASA technology been implemented promptly in a massive retrofit program. The arguments made against implementation were largely economic. In light of the rapid rise in fuel prices, it is appropriate to reexamine the issue.

6.4 NASA'S POTENTIAL IMPACT

Section 6.2 noted that the FAA's cost-benefit analyses showed that REFAN was among the least cost-effective options, and largely on this account it was dropped as the basis for regulatory action. A key factor in the low cost effectiveness was the fact that operating costs for REFANned aircraft were projected to increase by about 2.4 percent for both the B-727 and the DC-9.[225] Less than five years later, however, McDonnell-Douglas launched the MD-80 series, a stretched version of the DC-9 using JT-8D-209 engines, the production version of the JT-8D-109 REFAN. What happened to reverse the attractiveness of the REFAN?

Figure 6-6 plots the thrust of various engines against noise (what I have termed Thrust-Specific Noise Production, or TSNP, the noise level in EPNdB theoretically produced for one pound of thrust). The JT-8D series used on the B-727s produce between 14,500 (JT-8D-9) and 16,000 (JT-8D-17) pounds of thrust. The JT-8D-209 produces about 20,000 pounds of thrust. Due primarily to its higher bypass ratio, the -209 produces less noise and consumes less fuel per unit of thrust. Unfortunately, the higher thrust cannot be utilized appropriately if the engines are fitted onto existing aircraft. Instead, they pose a slight operating penalty.

225 *Aircraft Noise Abatement*, December, 1973, p. 85.

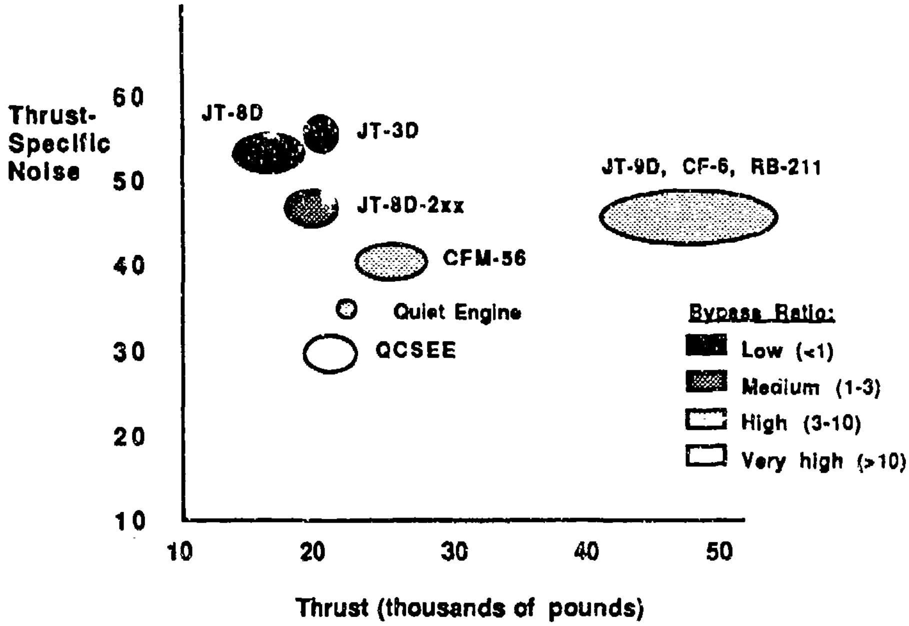

Figure 6-6. Design thrust versus specific noise level for various modern commercial jet engines. These figures are the author's calculations based on sideline noise at takeoff thrust.

There are two options for resolving this: either the engine size can be reduced or the aircraft size can be increased. Neither of these options was seriously considered during the debate about FAR-36. With the MD-80 McDonnell-Douglas took the second option, stretching the DC-9 about 14 feet. The large fuselage is now well matched to the increased thrust, and 20 additional passengers can be carried for essentially the same fuel bill. It is the extra seats in addition to the lower specific fuel consumption that provide much of the leverage that makes the MD-80 so cost effective.

This strongly suggests that the REFAN's low cost effectiveness was due not so much to its incorporation of noise reduction features as to the fact that it was poorly sized for its intended market. REFAN faced the classic identity problem of NASA aeronautics programs. It was originally conceived as a prototype for an engine that could actually be retrofit onto existing aircraft. Cost reduction pressures quickly made it more of a "proof-of-concept" experiment. As such, exact sizing was not nearly as important as low cost. The FAA and other potential users, however, judged the engine as if it was a prototype that could be placed directly into production. Thus, while NASA was demonstrating *levels of technology*, the cost-benefit analyses were being conducted with literal REFAN characteristics.

There are at least three reasons why the private sector was apparently content to let this inconsistency pass. First were the general economic conditions. The early 1970s were a time of hardship for the airlines, who had invested heavily in wide-body equipment only to face a serious recession that resulted in great overcapacity. The second reason was that all the manufacturers had a growth orientation that predisposed them to build new, larger airplanes and engines. Everyone assumed that the next generation of small aircraft would be larger than the current generation. Thus, Boeing designed the 180-seat B-757 to replace the 120-seat B-727, and Douglas designed the 150-seat MD-80 to replace the 120-seat DC-9s. They wanted to build new designs or stretch existing ones. To refit existing designs, or worse, existing aircraft, would delay the introduction of new aircraft. Finally, there was continuing uncertainty among all the airframe and engine companies as to exactly what standards would be promulgated by the FAA.

It is somewhat more surprising that NASA and the FAA talked completely past each other: NASA was developing levels of technology, and the FAA was regulating on the basis of specific designs. If the FAA had been willing to regulate on technology levels, then the NASA program would have been completely appropriate. As long as the FAA insisted on regulating on the basis of specific designs, then the NASA program should have focused on providing data and alternatives that were properly scaled for retrofit. Either option would have supported the conclusion that the FAR-36 limits could have easily been lowered at least 10 and probably 15 EPNdB.

Had the government actually forced the industry to adopt the stricter noise levels, and thus, retrofit with a properly sized engine, the private sector would probably have made money. This surprising conclusion is based on two crucial factors: first, that a properly sized engine would have been more economical to operate, and second, that the rapid price rises that occurred during the later 1970s would have dramatically increased the payoff.

Assuming an average utilization of 8 block/hours per day and a gross fuel consumption of 1200 gallons per hour,[226] and the actual fuel prices for 1975-1985, the average savings from each option can be computed. Figure 6-7 plots the airline's effective internal rate of return (IRR) as a function of the required initial purchase price for quiet engines. According to the author's calculations (see Table 6-5), a properly-scaled REFAN

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226 See "Narrow-Body Aircraft Direct Expenses--Second Half 1983," AW&ST, August 13, 1984, p. 45.

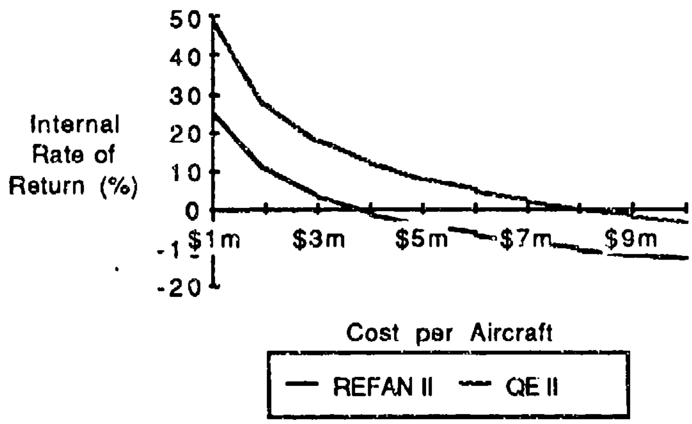

Figure 6-7. Internal Rate of Return versus investment cost for two properly-sized quiet engines. The "REFAN II" has the performance of the JT-8D-209 at the thrust levels appropriate for a B-727. The "Quiet Engine II" has the performance of the CFM-56 at the lower thrust levels.

Table 6-5. Characteristics of Hypothetical Follow-On Engines

	Noise		Fuel Consumption	
	TSNP[227]	%	TSFC	%
JT-8D	58	1.0	0.62	1.0
REFAN II	48	0.83	0.51	0.82
Quiet Engine II	35	0.60	0.38	0.61

(here called "REFAN II") could have cost up to about $2.5 million per aircraft and allowed IRRs of 6 percent; net present values remain positive up to about $3.5 million (the NASA REFAN I was projected to cost about $1.7 million per shipset;[228] in 1988 the Valsan modifications to 727s that replace the outboard engines with JT-8D-200 engines modify the center engine cost about $8.5 million,[229] or about $3.2 million in FY72 dollars). Quiet

227 Thrust specific noise production, defined here as the noise level theoretically produced per pound of thrust. It is calculated as: TSNP = EPNdB − 10 log(thrust in lb).

228 *Aircraft Noise Abatement*, December, 1973, p. 76.

229 "Valsan Flight Tests First Reengined 727-200," *Aviation Week & Space Technology*, August 8, 1988, p. 76.

Engine IIs (a version of the NASA Quiet Engine scaled to 15,700 pounds of thrust) could have cost up to $7 million per shipset while still retaining positive net value. On engines that were retrofit, these "investment values" reflect the cost of the new hardware minus the residual value of the replaced engine or parts. On new aircraft, where the airline would be buying new engines anyway, the investment value represents the cost *increment* that could be justified for the new model engines. These rates of return are fully appropriable to the airlines, and do not include the social benefits of noise reduction.

The airlines and manufacturers both argued that in retrofit there would be an inevitable opportunity cost; that retrofitting old aircraft would delay the introduction of new models. Four essentially new American airliners (B-757, B-767, B-737-300, MD-80) have been introduced since the retrofitting alternative was abandoned, and it is worth examining briefly how each might have faired had retrofitting gone ahead. The Boeing 767 was aimed at a larger market and would have been unlikely to have been affected by a retrofit decision. The B-757 was intended to be a replacement for the B-727, and it might well have been delayed had a retrofit been ordered for the 727 (Boeing had actually planned such an aircraft, the 727-300). The 757 has been used by the airlines more as replacement for the B-707 and B-720 than for the 727; its sales have been comparatively slow and its delay might not have been an altogether undesirable thing. Both the 737-300 and the MD-80 are powered by engines inspired by NASA programs (the 737-300 uses the CFM-56, the heir of NASA's Quiet Engine, while the MD-80 uses the JT-8D-209, the production version of REFAN) Both of these aircraft might actually have been available *sooner* given an aggressive retrofit program, since retrofit would also have required modification of existing production models.

6.5 CONCLUSIONS

By the early part of the 1970s, NASA had demonstrated the technology for substantial reductions of aircraft noise. Some of this technology originated from within NASA but much was developed elsewhere; NASA's chief accomplishment was to pull the various elements together and to integrate them into a workable system. NASA had developed the technology, but never established a clear mandate to go beyond that to the true prototype level.

The FAA and the EPA acted essentially as administrative agencies, promulgating rules and making decisions largely on the basis of an existing, rather than potential, situation. The regulatory agencies treated NASA's results as prototypes. This led to a decision not to set noise standards at levels and timetable that would force engine retrofitting. Although the noise levels did decline following the implementation of Federal regulations, the decline was only about one third what could have been achieved with full implementation of the NASA results.

The arguments made against full implementation of the NASA results were based primarily on the economics of retrofitting and especially where the money required for retrofitting would come from. As it turned out, the rapid increases in fuel prices that occurred during the latter half of the 1970s meant that the airlines would have been better off economically with retrofitted engines, which would have been not only quieter but also more fuel efficient.

There are many factors, of course, that limit the general utility of the noise case as an example for future policy. The rapid price rises were unforeseen (and probably unforeseeable) by both government and industry. But the general behavior of the various parties probably was typical, and from this, several general conclusions can be drawn.

First, the private sector can be expected to oppose proposed regulations. No airline sought to turn the noise retrofit issue into an advantage by seeking government assistance in upgrading their fleets.

Second, the noise case suggests that government regulatory agencies will normally act as adjudicatory bodies, choosing between options currently available. This is particularly true in cases such as noise where the pollution levels ultimately acceptable are ambiguous.

These observations suggest a cycle of inactivity, whereby the regulatory agency is reluctant to propose standards that have not already been proven, while the industry has no incentives to demonstrate levels that have not already been mandated. The very long development cycles (seven years is a typical period for an engine development program) further complicate the situation. It is difficult enough for a private company to attempt to deal with technological and market uncertainties seven years in the future. Expecting them to absorb the risks of projecting government policy seems unreasonable. One way of breaking this cycle is by having an independent party, such as NASA, take the initiative to develop new technological options. This worked in the noise case, but apparently not as well as it could have. Again, there appear to be three basic issues.

The first issue is timing. Ideally, a thorough understanding of the technology should precede regulatory effort. In noise they were pursued in parallel, largely because

NASA was reluctant to move into the area until forced to do so by the Executive Office. NASA allowed the R&T Base in noise reduction to deteriorate during the early 1960s, which delayed their ability to mount effective responses once given an Executive mandate in 1965. The Noise Reduction Laboratory at Langley, for example, was not opened until 1972.

The second issue is scope of demonstration. In the noise case, NASA went further down the R&D spectrum than it had ever gone before in terms of civil aircraft, and this produced great internal resistance to programs such as REFAN. Yet in retrospect, the problem with these programs is not that they went too far, but that they did not go far enough.

The third issue is coordination. NASA developed good demonstrators, while the FAA treated them as prototypes. This clearly requires better coordination between the agencies: either NASA should have been building true prototypes, or the FAA should have based their regulations on "rubber engines" parametrically based on the NASA results. In general, this type of overall coordination (which sounds simple and obvious in theory) seems to be best imposed from above, in this case, a central monitor in the Executive Branch. The noise program was never more vigorous and balanced than when the Office of Science and Technology was in control between 1965-68.

One theme consistently evident through the public policy literature is the idea that the private sector understands the market better than the government and the government should stay out of market-related decisions. The aircraft noise reduction example does not support this conclusion. For one thing, the government controlled the market. The major driver in the noise case was regulatory levels, which the government was in a much better position to anticipate than the private sector. When the government controls the market, the government should absorb some of the risk. Even so, it should have been obvious to the private sector that there was a need for small-sized, high-bypass-ratio engines. The three major engine companies (General Electric, Pratt &Whitney, and Rolls-Royce) all concentrated on the development of essentially redundant large high-bypass turbofans, while collectively leaving the small high-bypass fan engines, which would have had such high social payoffs, virtually untouched. NASA took the first steps towards filling this gap with its Quiet Engine Program, but the program was never pursued. When the engine manufacturers did build smaller engines, they tended to follow specifications set by NASA: the GE CFM-56 was sized exactly at the thrust level of NASA's Quiet Engine, while the

Pratt & Whitney JT-8D-209 is only slightly higher thrust than the REFAN. Even today, there is no high-bypass engine in the thrust range of the original JT-8D.

NASA is limited in its influence, however, and this example perhaps argues for a high-level interagency group such as the National Aeronautics & Space Council. The Department of Defense with its large fleet of KC-135s represented a major market for retrofitting. DoD's aircraft were not technically subject to FAR-36, however, and reengining was given a consistently low priority. A high-level council could have assessed this situtation for the national opportunity it was: NASA's low-noise technology could have been brought to market by an early government commitment to re-engine its own aircraft. This would have saved the government considerable fuel costs, set an example by reducing aircraft noise in the government's own fleet, and provided a retrofitable quiet engine to the commercial market.

Finally, the noise case illustrates how R&D investments can produce benefits outside their primary goal. The power of R&D as an investment is demonstrated by the MD-80 and its role in keeping the McDonnell-Douglas Corporation in the commercial airliner business. Between the crash of a DC-10 in 1979 and launch of the MD-11 in December 1986, 90 percent of McDonnell-Douglas's sales volume was for the MD-80 with its JT-8D-200 series engines. It is probably not an exaggeration to say that this aircraft allowed McDonnell-Douglas to stay in the commercial airline business at a time when it otherwise might have had to pull out. The $40 million NASA invested in REFAN (about the cost of a single MD-80) seems like quite a bargain in terms of preserving competition within the aircraft manufacturing industry.

CHAPTER 7. R&D COOPERATION FOR MILITARY AIRCRAFT

The important role of aircraft in the modern military and the rapid rate of technological change in aeronautics and related fields ensures that the Federal government has a strong interest in aeronautical R&D. That such interest is appropriate has been thoroughly documented elsewhere and is not at issue here.[230] Rather, this chapter considers the circumstances under which NASA, rather than the Department of Defense (DoD) or its private contractors, should conduct aeronautical R&D with probable military applications.[231,232] This will be done by examining three examples of NASA/DoD interaction, in powered lift (STOL), vertical lift (VTOL), and hypersonics. The reader should note that these cases have been studied from the NASA perspective, and that the focus is on the role of research aircraft. Further study from the DoD perspective may be advisable.

The general picture that emerges is that NASA's most important contribution is in conducting focused research programs that provide the basis for radical departures from existing technology. Translating these advances into operational systems, however, frequently requires the use of experimental flight vehicles,[233] for which NASA, by itself, lacks sufficient resources. The services tend to emphasize prototypes more than research aircraft, which is appropriate but sometimes leads to confusion between the two, especially in Congress and other outside observers, and sometimes within the programs themselves. In true prototypes little NASA role seems to be called for, whereas for research aircraft

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230 Among others, see Office of Science and Technology Policy, *Aeronautical Research and Technology Policy* (Executive Office of the President, November 1982).

231 Opinions on this subject range from the extreme that military benefits are the only justification for NASA aeronautical R&D to the idea that a civilian agency like NASA should avoid any semblance of military research. The NACA is the model cited by the former; the NASA space program is an example of the latter.

232 There is also a small component of aeronautical research supported by the National Science Foundation, but it is only on the order of $1 million per year and is not considered here. See National Research Council, *NASA-University Relationships In Aero/Space Engineering* (National Academy Press, 1985), Appendix A.

233 Broadly defined here to include "proof-of-concept," "demonstration," and "technology validation" programs.

NASA technical leadership in a cooperative program appears to be the most successful route for developing and transitioning technology into military systems. Since research aircraft tend to be large and expensive compared with other elements of the NASA aeronautics program, they must be carefully thought through, and require support from the top levels of NASA management.

7.1 THE R&D TRIAD

During most of its lifetime, the NACA held almost exclusive responsibility for the government's aeronautical research, including that intended for military applications. Following the Second World War, the services dramatically increased their involvement with R&D.[234] In 1958, most R&D was consolidated under the Under Secretary for Defense Research and Engineering (USDR&E, more commonly DR&E), and the Advanced Research Projects Agency (ARPA, now DARPA) was formed to pursue high-risk programs.

As discussed in Chapter 1, DR&E funding is divided into five categories ranging from Research to System Development. Much of this funding is devoted to the development of specific operational systems (such as the F-15, B-1, etc.), and thus does little to advance technology in general. The categories of Research (6.1), Exploratory Development (6.2), and part of Advanced Development (6.3a) are frequently grouped together as the "technology base," and it is this funding which is generally considered comparable to the work undertaken by NASA.

In addition to this "directed" R&D conducted by DR&E, the Department of Defense reimburses contractors for some of their own R&D costs under the Independent Research and Development (IR&D, or IRAD) program. This "undirected" R&D is considered to be a part of each contractor's legitimate overhead, although spending levels are negotiated separately and in advance. IR&D covers company-directed research and development not required in support of a specific product or contract; it is treated as overhead on production contracts by DoD. The program is politically controversial since it represents government-funded R&D that is conducted outside of the normal R&D review and approval system.[235]

234 At least part of this increase appears to have been in response to NACA's slow progress relative to the Germans, especially in such areas as turbojets and high-speed flight.

235 See National Research Council, *The DoD-NASA IR&D Program: Issues and Methodology for an In-Depth Study* (National Academy Press, 1981).

Detailed summaries of corporate IR&D are compiled annually by each company as part of the government reimbursement process, and these are maintained in the IR&D Data Bank maintained by the Defense Technical Information Center in Alexandria, Virginia. These summaries provide a means for estimating the scope and direction of the IR&D effort, though not its funding level.[236]

Both the DR&E "technology base" and the aeronautics IR&D appear to be roughly comparable in size to the NASA aeronautical R&D effort (see Figure 7-1). This invariably raises questions about how the programs relate to each other, how they are coordinated, and whether there is redundancy in the government's military aeronautical R&D effort.

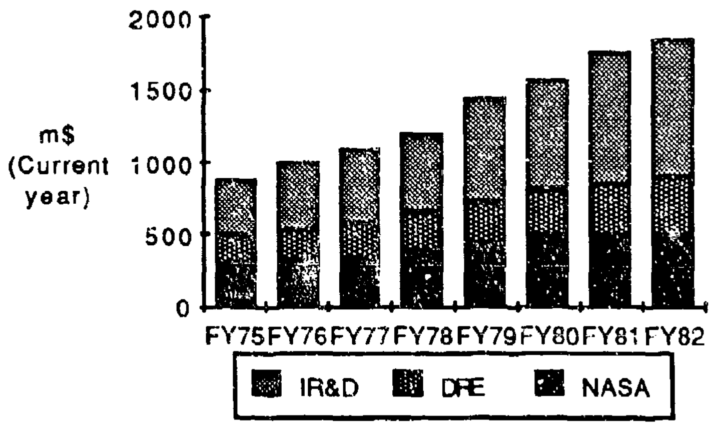

Figure 7-1. Total U.S. funding on aeronautical research and technology, as estimated by Office of Science and Technology Policy for years 1975-1982. Note the significant importance of IR&D. Although these data are probably the best available, they should be regarded as extremely tentative, especially the IR&D values.
Source: OSTP, *Aeronautical Research and Technology Policy*, November 1982. Figures VI-1 and VI-9.

236 The dollar values associated with specific companies and specific research areas are closely guarded proprietary information. The only financial data available on IR&D spending are the gross totals released each year in Congressional testimony. The National Science Foundation does report dollar values for company-funded R&D by industry, but this data is confused by the lack of consistent use of the term "independent research" regarding the distinction between the reimbursed and unreimbursed portions. Thus, for example, most of the data reported to the NSF as "company-funded" research is actually total IR&D, which in some aerospace companies is over 80% reimbursed by the government. See Judith Reppy, "Defense Department Payments for 'Company-financed' R&D," *Research Policy 6* (1977) 396-410.

There is a long history of formal coordination between NASA and DR&E. To coordinate between the NASA and DoD programs, the Aeronautics and Astronautics Coordinating Board (AACB) was established in September 1960. The AACB continues to operate, with the goals of facilitating planning, coordinating research where possible, identifying problems of mutual interest, and in general avoiding duplication. There is no similar formal mechanism for coordinating the NASA effort with private sector IR&D. To examine the questions of how the programs interact in practice, whether they compete with or complement each other, and whether a NASA role is truly justified in military aeronautics requires the examination of specific case studies. Two of the examples that follow, the STOL and hypersonic programs, were introduced in Chapter 3. A third case, that of VTOL, has been added here as an example of complementary programs.

7.2 STOL RESEARCH: DETRIMENTAL COMPETITION

Short takeoff and landing (STOL) capability seems like an area with obvious overlap between commercial and military applications. Commercial STOL aircraft could use small airfields near city centers, while military STOL transports could operate from short impromptu fields close to the front lines. This dual nature would seem to make STOL technology the perfect candidate for a closely coordinated program between NASA and the DoD. In fact, STOL is an example of a technology that perhaps looked *too* attractive, which resulted in a premature split between civil and military aircraft. Despite five major experimental aircraft programs during the 1970s (3 by NASA and 2 by DoD), none have yet led to an operational aircraft (although the C-17, with externally blown flaps, is under development).

As discussed in Section 3.2, NASA and the services had all been actively supporting military STOL and VTOL concepts for many years before NASA began its technology development program aimed at civil aircraft in the late 1960s. At the time the NASA program began moving into proof-of-concept aircraft with the Augmentor Wing, Air Force interest was at a low ebb and the first NASA designs were partnerships with the Army and the Canadian government. When the Air Force became interested in a possible replacement for the C-130 in about 1970, they began by surveying the data base prepared by NASA, and designing a research program to fill perceived gaps.

By 1972 both NASA and the Air Force agreed that a flight vehicle was desirable; in the early 1970s no turbofan powered-lift vehicle had ever flown and none of the leading concepts had ever been tested in flight. Although there was some disagreement over the best concept to be used (NASA preferr the Augmentor Wing, the Air Force liked externally blown flaps), the primary disagreement was over the proper size and use of the vehicle. NASA wanted to build a small, versatile "proof of concept" research aircraft that would provide information on a variety of questions, while the Air Force wanted a prototype that could be pressed rapidly into production.

In January 1972, the Assistant Secretary of the Air Force for R&D (Grant Hansen) and the Associate Administrator for OAST (Roy Jackson) signed a STOL agreement whereby NASA would concentrate on a small (50,000 lb) research vehicle and the Air Force would concentrate on a larger (150,000 lb) prototype. To promote communications they established a STOL Aircraft Coordinating Council, and agreed to cross-assign engineers to each other's programs.[237] The NASA vehicle became known as QUESTOL (see Section 3.3), while the Air Force vehicle became the Advanced Medium STOL Transport (AMST).

When the Air Force issued its request for proposals (RFP) for the AMST in 1972, it emphasized that one of the major factors to be considered in the evaluation was how rapidly the contractors could implement their vehicles into production. This had a number of implications. First, it led to conservative designs, such as the use of lower lift coefficients or existing engines. Second, it tended to make the designs rigid rather than flexible. Finally, it actually discouraged contractors from considering factors (especially noise) that were important for civil applications but not for military ones.

Despite the lack of civil considerations, formal go-ahead on the AMST prompted the Office of Management and Budget (OMB) to terminate QUESTOL. NASA subsequently signed an agreement with the Air Force giving them the option to purchase an additional AMST, or to participate in Air Force flight tests.

In 1978 the AMST itself was cancelled, apparently due to its high cost relative to the C-130. Following the cancellation, both Boeing and Douglas investigated possible commercial options for their prototypes. They found that the military AMSTs were poorly suited for commercial markets, especially since their slow speeds (Mach .7 due to unswept wings) imposed productivity penalties. The STOL experience was also a bitter experience for the private contractors involved and probably discouraged independ investme on ...ical new concepts. All three major contractors invested their own development money

237 See *FY73 Authorization Hearings* (92/2 1972 V2).

in government-proposed vehicles only to have the vehicle cancelled: Lockheed invested several million dollars on QUESTOL, Boeing provided some $50 million on the AMST, while McDonnell-Douglas provided a similar amount on the YC-15.[238]

Even as the AMSTs were flying, NASA was completing the much less expensive Quiet STOL Research Aircraft (QSRA). QSRA began flying in 1978, but as discussed in Section 3.2 it came at a time of declining general interest in STOL (the same year QSRA was delivered NASA cancelled most STOL activity in the R&T base) and to date has had little impact on other American programs.

The cancellation of QUESTOL was clearly related to the perceived parallel nature of the AMST. The cancellation of the AMST was less clearly related to technical problems, but created the paradoxical situation of the "research vehicle" (QSRA) flying several years after the "prototype" (YC-14). The whole situation illustrates, however, the difficulty of sustaining separate R&D programs, and the need for continuous R&T work on alternate possibilities in the same area.

Several points should be made in conclusion. First is the tendency of operational agencies to shift from low levels of interest and support to high levels of activity aimed at securing operational vehicles (the preliminary design phase of the AMST, for example, allowed only 90 days, implying no design-specific R&D, and hence, use of the existing technology base).[239] Such extremely rapid shifts leave little time for the systematic development of a technology base, and thus either build a large element of conservatism in the design or increase the development risks. This suggests the need for NASA to independently anticipate the future needs of the services. Operational agencies clearly tend to emphasize prototypes rather than research vehicles. This results in exclusion of considerations such as noise that are important to the civil sector. Finally, the case illustrates the difficulty that NASA has in gathering enough institutional support for its own flight research aircraft. QUESTOL was cancelled by OMB almost as soon as the Air Force decided to proceed with AMST, despite NASA claims that only about 25 percent of the flight research goals of QUESTOL could be met by AMST.

All of these suggest that a dedicated R&D agency like NASA is better suited to develop and operate research aircraft, but that it must take the initiative to do so.

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238 See "Boeing, McDonnell-Douglas Eye Continued AMST Development," *Aviation Week & Space Technology*, January 16, 1978, p. 29.

239 *Jane's All the World's Aircraft, 1975-76*, p. 290.

7.3 VTOL RESEARCH: A MODEL OF COOPERATIVE PARTNERSHIP

In contrast to the STOL effort, where five research aircraft have produced no operational vehicles, the NASA/Army program in Vertical Takeoff and Landing (VTOL) appears to be a model of success and cooperation. The proof-of-concept XV-15 Tilt Rotor has led to the development of the V-22 Osprey, a $2.1 billion development program aimed at producing more than 900 aircraft for all four armed services. If development of the Osprey is successful, NASA will have made one of its most important contributions ever to military R&D, one with many probable civil applications as well. Although VTOL was not examined in the Case Studies of Chapter 3, it is worth a brief examination here for the contrast it poses to STOL.[240]

Although NACA conducted some autogyro research during the 1930s and NACA/NASA participated extensively in the testing of the Tri-Service VTOL aircraft in the early 1960s, NASA's current role in rotorcraft research stems from 1965. That year NASA and the Army signed a joint agreement and established an Army Aeronautical Research Laboratory at Ames Research Center. During the next five years, NASA's rotorcraft budget increased steadily as it worked with the Army to pursue topics of common interest, primarily in the areas of blade aerodynamics and structural dynamics of rotors. In 1970 the Army established Army Aviation R&D Command (AVRADCOM) at Ft. Eustis, Virginia, and joint agreements were extended to include Langley and Lewis.[241] In 1972, NASA and the Army agreed to jointly fund two experimental aircraft, the Tilt Rotor Research Aircraft (TRRA, aka XV-15) and the Rotor Systems Research Aircraft (RSRA). These cooperative programs have both enjoyed long and apparently productive lives, and are highly regarded as effective examples of cooperation.

The Tilt Rotor resembles a conventional aircraft, except that its two engines are mounted at the wingtips and drive extremely large three-bladed propeller/rotors. For vertical operations, the engines are pivoted vertically and the blades act as twin rotors. Once airborne, the engines are gradually rotated into a horizontal position, with the propellers now supplying forward thrust and the wings providing the vertical lift. This configuration offers VTOL capability combined with high forward speeds. Between 1978 and 1985 the 13,000 pound XV-15 underwent more than 530 hours of flight testing,

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240 It should be noted that this review is by no means exhaustive. In particular, the work that led to the operational VTOL fighter, the *Harrier*, is not discussed.

241 Office of Aeronautics and Space Technology, *Advanced Rotorcraft Technology: Task Force Report*. October 15, 1978.

reaching speeds of up to 345 knots and altitudes of up to 26,000 feet. The success of the Tilt Rotor led directly to the concept of the JVX, which in 1985 became the V-22 Osprey. Currently under development, more than 900 of these aircraft are planned for acquisition through 1999, including more than 500 for the Marine Corps, 50 for the Navy, 80 for the Air Force, and 200-400 for the Army.[242]

The Rotor Systems Research Aircraft was conceived as a highly modified, highly instrumented test bed that could be used for flight testing various rotor concepts. Based on a Sikorsky S-61 helicopter, the RSRA has conventional wings with flaps (used to unload the rotor and vary the horizontal forces), auxiliary forward propulsion, an electronic stability augmentation system, and extensive on-board instrumentation. The RSRA was completed in 1977, and was used for a variety of tests. In 1981 it became the testbed for the X-wing, a stopped-rotor concept whereby a four-bladed rotor is spun for VTOL operations but then stopped in flight to form two swept-forward and two swept-aft wings. Extensive circulation control (via air blown from both leading and trailing edges) allows the use of symmetrical blades and the elimination of mechanical pitch or aileron controls. Although the X-Wing has recently experienced funding difficulty, it holds great promise for future development.[243]

The Army/NASA partnership appears to be a model of how effective cooperation can produce benefits for the entire national defense community. There appear to have been three critical elements to this partnership. The first was collocation. By collocating its helicopter R&D centers, the Army was able to take advantage of NASA's existing technology and facilities. This efficiency was supplemented by the resulting short lines of communications. The second key was a set of clearly defined, mutually acceptable experimental goals. The goal was to explore radical concepts, rather than to build prototypes. The third key was clearly defined and distinct institutional roles. The Army viewed itself primarily as needing a tool to do a job; they understood the requirements and the conditions that the vehicle needed to operate under, but did not attempt to predetermine technical solutions. NASA, on the other hand, was responsible for ensuring that the research was technically innovative.

An important benefit that is difficult to quantify is the important political support that the two institutions were able to provide for each other's program. By coupling their

242 Mark Lambert, "V-22 Osprey: The Aircraft for All Seasons," *Interavia*, December 1985.

243 Mark Lambert, "X-Wing: Harrier Speed and Helicopter Hovering," *Interavia*, May 1985.

programs, NASA and the Army have been able to provide bureaucratic support to each other in Congressional and Executive reviews. NASA is able to point to the needs and participation of the Army to support its research requirements, and the Army is able to cite NASA's role to lend credibility to its research. Both the RSRA and the XV-15 are now entering their fifteenth year, testimony to the durability of the partnership.

7.4 HYPERSONICS: CAN RESEARCH AIRCRAFT BE JUSTIFIED?

In many ways, hypersonics appears to represent the "classic" model of a NACA/NASA aeronautics program: research pursued to push performance higher and faster, and the military takes over once a specific match between technology and mission has been identified. Indeed, hypersonic flight was always planned as "Round Three" of the NACA high-speed flight research program.[244] That Round Three never materialized was due to a combination of factors. As the Hypersonic Research Engine (Section 3.3) illustrates, the technology proved more difficult and expensive to develop than was originally envisioned. To some degree, many of the missions originally envisioned for hypersonic aircraft have been accomplished by other means (especially vertical-launch rockets) that proved less expensive in the shorter run.

The January 1986 announcement by President Reagan that the United States would pursue manned hypersonic aircraft through the National Aerospace Plane (NASP) both followed this traditional model and at the same time initiated a major departure from it. To the extent that NASP is based on technology provided by ongoing NASA programs, it is a success for the agency and illustrates the continued viability of the traditional partnership. To the extent that NASP is to become a research aircraft, however (as reflected by its designation as the X-30), it represents a significant departure, since it did not originate within NASA and in fact has only the qualified endorsement and limited participation of the agency.

This situation points out major strengths and weaknesses in the NASA aeronautics program. The strength is NASA's ability to conduct and sustain a focused research program over long periods of time without regard to the immediacy of its application. Section 3.3 discussed the extremely cyclical nature of Air Force interest in hypersonic

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244 Round One was the X-1 series, Round Two became the X-15, and Round Three was to be the X-20 class but was never implemented. See Richard P. Hallion, *The Path to the Space Shuttle, The Evolution of Lifting Reentry Technology* (Air Force Flight Test Center Historical Monograph, November 1983).

flight, which tends to alternate between peaks of enthusiasm aimed at procuring an operational vehicle as soon as possible (the Aerospaceplane in 1958, Project Forecast in 1963, Project Forecast II in 1985) interspersed with periods of almost total neglect. Although the NASA interest, too, has been cyclical (corresponding generally with the level of interest in next-generation space launch vehicles) the technology base effort has been somewhat more consistent.

The major NASA weakness pointed out by NASP is the difficulty in moving from focused technology into operational systems without premature commitment to an operational system and the excessive inflation of expectations that the latter frequently entails. In the early 1960s and the middle 1970s NASA attempted to initiate programs that would flight test hypersonic hardware on a research vehicle, but each time the effort failed to gather sufficient institutional support. The issue of whether it is possible in today's political environment to make a logical transition from focused technology into operational systems is critical.

Three analogies that seem relevant here (all involving high-speed aeronautics) are the X-20 Dyna-Soar, the Supersonic Transport (SST), and the Space Shuttle. The X-20 was originally conceived as a technology demonstrator. Of the nine proposals received from contractors in 1957, however, the two that were selected by the Air Force were the two that promised fully orbital vehicles that could be placed into operational roles. As the program developed, it became clear that the missions envisioned for the Dyna-Soar could, in the near term at least, be met far less expensively and more effectively by other means. Once the promise of operational missions was abandoned the program was too expensive to be justified by its research benefits alone, and the X-20 was cancelled in December 1963.[245]

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245 In his review of a draft of this manuscript, Dr. A.H. Flax (who at the time of X-20 cancellation was Assistant Secretary of the Air Force for Research and Development) stated: "The X-20 Dynasoar was not cancelled because of any technical problem or because the Air Force did not steadfastly support its status as a research vehicle. It failed because NASA top management, especially Deputy Administrator Dr. Hugh Dryden, who opposed the militarization of man in space and feared competition with its own Mercury/Gemini manned spaceflight program, withdrew its support and attacked it. OSD then demanded that the Air Force justify it as an operational system, which it was not." A case study by the Air Force Historical Office (see Clarence J. Geiger, "Strangled Infant: The Boeing X-20A Dyna-Soar," in Richard Hallion's *The Hypersonic Revolution*) offered a different interpretation, concluding "NASA..by no means concurred with the proposed termination of the X-20. Dr. Ray Bisplinghoff, Associate Administrator for OART, pointed out that advanced flight system studies had repeatedly shown the importance of developing the technology of manuverable hypersonic vehicles with high-temperature, metal-cooled structures" (p. 306).

A similar experience befell the American SST. In this case, the program grew out of a Presidential mandate and was structured around producing operational vehicles. As development proceeded, it became clear that the technology for an economically efficient, environmentally acceptable vehicle was not nearly as well developed as had been envisioned. Like the X-20, the cost of completing operationally-capable aircraft once their primary missions were abandoned could not be justified by research arguments alone. Although there would probably have been important benefits to completing and testing one demonstrator aircraft, the entire program was cancelled in 1971.

The Space Shuttle is yet a third example of a case where operational requirements were placed upon an experimental vehicle, to the detriment of both. In this case, NASA itself is the operational agency. The Shuttle was sold, with Presidential backing, as a cost-effective replacement for expendable launch vehicles. In contrast to the American SST, the Shuttle went through development and into operation. It took the tragic *Challenger* accident in February 1986 to remove the public veneer of an operational system and restore the reality that the Shuttle was experimental in nature. By this time, however, the national commitment to the Shuttle was so large that it consumed all available resources, making an improved second-generation system much harder to initiate or to justify.[246]

All of these cases suggest the difficulties of justifying experimental vehicles, and the resulting tendency to sell them as operational vehicles.

7.5 CONCLUSIONS

The three case studies examined in this section support a series of six general conclusions. The first is that one of NASA's most important roles is conducting focused research programs. In all three cases, important DoD development programs have been launched from NASA focused technology programs. The Air Force AMSTs both used powered-lift concepts developed by NASA. The technology in the tilt rotor and the X-wing grew out of work originally pursued in NASA. The current National Aerospace Plane effort is possible only because NASA maintained a small but continuous effort in hypersonics research.

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[246] This is not to suggest that a small-scale precursor to the Shuttle would have been appropriate, but merely to note the institutional tendency to sell experimental systems as operational ones. Charles A. Donlan noted in a review of this manuscript that "During the development of the Space Shuttle, this [sub-scale system] was looked into very carefully. It was concluded that a small-scale flight vehicle would contribute little, if any, significant design data for the program." Internal IDA communication dated 12/10/87.

In evolutionary developments the Department of Defense appears to do an excellent job.[247] Where revolutionary advances are involved, however, the interests of the Department of Defense (and indeed, this conclusion may perhaps be generalized to include almost any operational agency) tend to be almost binary: either a "need" is perceived, in which case an operational vehicle is the top priority, or it is not, in which case it is difficult to justify any appreciable ongoing program. Further, when a concept is placed into development, it tends to discourage (rather than stimulate) focused technology development of alternative concepts because of a competition for resources and the institutional threat that future systems pose to current-technology systems (i.e., why not wait if a better system is foreseeable?).

This has led to confusion between experimental vehicles on the one hand and prototypes on the other. Selling an experimental vehicle for what it is requires cooridination, such as in the X-15 program. Attempting to evaluate it purely in operational considerations (as was done for the X-20 and seems to be how the X-30 has been sold) seems to be a recipe for disappointment. The tendency is to push for a prototype that can be transformed rapidly into an operational vehicle. This tendency raises the costs, and limits the utility of the vehicle as a research aircraft. It particularly excludes civil considerations, which may end up having important applications with very low marginal cost in the research program. Finally, it does not provide nearly the stimulation to the technology base that a true experimental aircraft provides.

For NASA and the services to pursue separate experimental programs in the same area, as they did in STOL, appears to be a recipe for disaster. Experimental programs, in general, have a difficult time attracting and sustaining institutional and political support. When there are multiple programs in the same area, they become overspecialized (as did QUESTOL) and split this already small base of support. The results have been detrimental to all programs.

On the other hand, partnerships in research aircraft seem to have been quite successful when experimental goals and institutional roles were clearly defined at the beginning and where no operational aspirations were placed on the vehicle. In the XV-15 this meant NASA leadership in design (in order to maintain the research orientation) but

247 Gas turbine engines for fighters, for example, have seen a steady increase in performance and reliability thanks to ongoing DoD support.

service participation to provide user input and support, and to pave the way for a prototype that would follow experimental success.

Finally, it is clear that in order for research aircraft to be developed, support is needed from the very top levels of NASA. From the national point of view, these aircraft are very inexpensive compared to premature commitment to an unproven system. They are, however, quite expensive compared to the other elements of the NASA aeronautics program and thus they tend to be resisted by middle-level managers who are working with fixed resources. It is difficult for non-technical decisionmakers (in the Congress, Executive Office, or DoD) to understand the important role played by research aircraft. Thus, it is essential for NASA top management to promote these programs, for if they do not take the lead, no one in the agency will.

CHAPTER 8. R&D FOR INTERNATIONAL COMPETITION AND COOPERATION

There is presently a great deal of concern about industrial competition and what, if anything, the United States government should do about it.[248] One common theme is that R&D should be used as a means of making American companies more competitive. The goal of this chapter is to pull together relevant lessons from the case studies and apply them towards a general philosophy for NASA. Three general points will be argued: (1) that the dynamic nature of technology and the important international interchanges that occur argue against efforts to restrict general access to NASA results; (2) that technology development has low effectiveness in countering production subsidies received by foreign competitors; and (3) that the desirability of international cooperation in NASA aeronautics programs depends on the specific circumstances but is sometimes warranted.

8.1 STOL: SHARED PROGRAMS ENSURE JOINT COMPETITIVENESS

Much of the pioneering work for powered lift was done outside of the United States. As noted in Section 3.3, boundary-layer concepts were initially studied in Germany, the Jet Flap was studied extensively in England during the 1950s, and many of the STOL configurations that NACA and NASA tested in the late 1950s and early 1960s were of foreign origin: the German Stroukoff YC-134, the Japanese UF-XS seaplane, and the French Breguet 941.

When NASA began to augment its powered-lift program in the late 1960s, one of the most promising concepts came from Canada. The Augmentor Wing had been proposed by DeHavilland in 1964, and tested in a series of models at NASA-Ames beginning in 1965. NASA and the Canadian Defense Research Board joined together to develop a "proof of concept" vehicle known as the Augmentor Wing Jet STOL Research Aircraft (AWJSRA, or Augmentor Wing). This program is an excellent example of how a mutually beneficial research program can be structured without the international transfer of funds.

[248] See, for example, the President's Commission on Industrial Competitiveness, *Global Competition: The New Reality*, Goverment Printing Office, January 1985.

NASA, working through Boeing, was responsible for the modification of a C-8 Buffalo (originally designed and built in Canada) into the AugWing testbed.[249] The Canadian Department of Industry, Trade, and Commerce contracted with DeHavilland and Rolls-Royce of Canada to provide the propulsion system, two Spey MK 801-SF engines modified to collect fan air and duct it through the wing while ducting core air through a vectorable nozzle. The aircraft made more than several hundred flights before being retired to Canada in 1978.

Despite this success, later NASA STOL projects were exclusively American projects. This was not for lack of other alternatives. The Japanese, for example, directly copied many features of the NASA QSRA when they began development of their *Asuka* in 1975.[250] Although built on NASA technology, the *Asuka* is designed to explore higher speed ranges and thus extends the experimental range.

The Soviet Union used the same upper-surface blowing technology in the development of their AN-72 transport. The AN-72 (and its operational cousin, the AN-74) resemble the Boeing YC-14 but are less than half the weight.

Together, the STOL examples suggest several conclusions. The first is that when a technology is easily transferable, as many of the basic concepts in aeronautics are, progress is made more through will and determination than through protectable insights. Just as the U.S. was able to build easily upon the earlier British, French, and German work, so the Japanese and Soviets have been able to build on and carry forward American research. Much of the technology is inherently not protectable; the state of the art is dynamic, and the only way to sustain leadership is through continued work.

The second clear lesson is that international partnerships in aeronautical R&D are practical. Although the Augmentor Wing was noisy and has yet to find an operational application, it led to further concepts for both partners. The AugWing allowed them to conduct research that neither might otherwise have been willing or able to pursue. Perhaps it is precisely the relative remoteness from commercial applications that made cooperation

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249 Among the changes, Boeing reduced the wingspan from 96 to 79 feet, added bi-surface augmentor flaps to 70% of the wing and blown ailerons to the rest, and installed the complex AugWing ducting. They also installed stronger landing gear, a stability augmentation system, an extensive data acquisition systems. See R.H. Ashleman and H. Skavdahl, *The Development of an Augmentor Wing Jet STOL Research Airplane*, NASA CR-114503, August 1972.

250 Down to the crook in the air data collection boom. The NASA boom had been installed at the incorrect angle and later bent to the proper angle. When the Asuka was rolled out, its boom featured the same distinctive bend!

possible, but it must be remembered that at the time the applications did not seem at all remote.

The present aeronautical research policy seems to ignore both of these lessons. Rather than encouraging joint research, for example, the White House Office of Science and Technology Policy has urged NASA to restrict foreign dissemination of its research results. Citing the Soviet AN-72 and the Japanese Asuka as evidence of damage to the national interest,[251] they have urged that foreign nationals be excluded from even unclassified conferences, and that distribution of unclassified papers be restricted. These actions ignore the fact that many of the same reasons that make government support of R&D appropriate in the first place make efforts to protect the results futile or counterproductive.

8.2 AIRCRAFT NOISE: R&D FOR INTERNATIONAL PROBLEMS

Like many environmental problems, the effects of aircraft noise are not limited to a single nation. Indeed, since the first application of commercial jet aircraft was on long-range international routes, the aircraft noise problem was a matter of international concern from the very start.[252]

As in STOL, much of the early technical work on noise reduction occurred outside the United States, particularly in Britain. The first comprehensive theory on the noise production of jets was developed by Lighthill in 1952, the first practical bypass turbofan (the Conway) was developed by Rolls-Royce in 1954, and the pioneering work on jet noise suppression was done by Greatrex in 1956. All of these developments were built upon when noise reduction became a heightened American concern in the later part of the decade.

The British also made important contributions studying the physiological effects of aircraft noise and the bases for regulation. In 1961 the British Government established (through the Wilson Committee) that the number of jet operations was more important than

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[251] The 1982 OSTP Report claims that "4 (AIAA) papers have been used by the Japanese in their development of QSRA-type experimental airplane" (p. VII-74), while both the OSTP report and Soviet Military Power cite the AN-72 as being "a copy" of the YC-14 (SMP, 1984, p. 110).

[252] The issue continues to be one of important international interest. For example, most of the requests for exemptions to U.S. noise standards are from small international airlines operating older equipment; they claim the burden of retrofitting or reequipping imposes an unfair penalty on them.

the absolute noise from each aircraft.[253] In 1966 the British Ministry of Aviation hosted an important International Conference on Aircraft Noise that for the first time brought together researchers and policymakers from around the world to address the problem and its potential solutions. This conference provided the consensus upon which the International Civil Aircraft Organization (ICAO) built its regulations.

Once NASA increased its involvement in noise reduction in the late 1960s the focus of research shifted to the United States, but British products continued to set operational standards for low noise. The Rolls-Royce RB-211 remains the quietest of the large turbofan engines, while the British Aerospace BAe-146 is the quietest commercial jetliner. The BAe-146 has been criticized by American companies for its overemphasis on low noise at the expense of efficiency, but the aircraft has been most successful in areas where local ordinances allow airlines to trade frequency of operation with individual noise levels (this is the Noise Exposure Forecast system, which the NAS urged in 1971, in practice. See Section 6.2).

Although American regulations drove early noise reduction efforts, international standards are playing an increasingly important role. Pressure for quieting late production models of the B-727-200 came from overseas, for example, rather than from domestic regulations. This trend is particularly important since, as noted in Chapter 4, the civil export market is considerably larger than the domestic market.

Despite this unquestionably international flavor, there seems to have been little coordination of noise reduction research at the intergovernmental level. This seems surprising, in light of the extensive contributions made by foreigners and the strong international aspect of the problem. The lack of joint programs has probably occurred for two reasons. First, NASA's priority has always been specifically to stimulate American companies. Prior to 1965 noise reduction research was a low priority at NASA, while after 1965 it was augmented with large programs aimed at improving existing aircraft. Most of these aircraft had been made by American companies, with whom the NASA programs were naturally coordinated. A second likely reason is that aircraft noise reduction was the subject of extensive coordination within the U.S. government. Participation in the many special review panels and study groups undoubtedly required a great deal of organizational effort, that otherwise might have gone into international cooperation.

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253 E.J. Richards, *A Historical Review of Aircraft Noise Suppression*, University of Southampton, August 1966.

8.3 HYPERSONICS: SHARING THE BURDEN

Although hypersonic research facilities exist in several countries, there have been no major hardware development programs such as the Hypersonic Research Engine or the X-15 undertaken outside the United States. Thus the field, by its early stage of development, offers fewer obvious lessons than the noise and STOL examples.

What hypersonics does seem to suggest is an opportunity. Skolnikoff has argued that there is the potential for mutually beneficial joint research any time that (1) high quality R&D capability exists in countries that share U.S. interests, (2) the problems facing those countries are common and intertwined, and (3) the costs of R&D are large relative to the ability of any one country to seek answers on its own.[254] Hypersonics appears to be such an area. It is clearly one of those high-risk, high-cost areas that nonetheless offers sufficient long-term promise (primarily for advanced space launchers) to warrant continued and widespread interest; it has the additional advantage that commercial applications are so far removed that direct commercial competition is not a major issue. The British have been exploring HOTOL (Horizontal Takeoff and Landing), a recoverable unmanned space launcher that uses a hypersonic, air-breathing propulsion system. The French are proposing Hermes, a conventionally launched, manned shuttle more akin to the X-20 DynaSoar. Germany, meanwhile, has proposed the Saenger, a two-stage shuttle system, with a rocket-powered second stage borne on the back of a hypersonic air-breathing first stage.[255] Individually, the amount each European partner is spending on hypersonics is small compared with the American NASP. Collectively, however, their contribution could be quite significant.

A common argument against international research is that whenever R&D has potential military applications it is better kept within the United States. Two opposing trends exist today. One is characterized by the Administration's efforts to control technology transfer, which spill over into a chilling of intergovernmental technology development programs. On the other hand there is an increasing enthusiasm for sharing the defense burden between the Western Allies, including the R&D burden. The Nunn Amendment is perhaps the latest example encouraging joint development programs. Hypersonic R&D appears to be an excellent candidate for such cooperation.

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254 E.B. Skolnikoff, *International Science and Technology Activities of Domestic Departments and Agencies*, Office of Science and Technology Policy paper, September 1979.

255 "Saenger joins Hermes and HOTOL," *Flight International*, 13 September 1986, p. 62.

8.4 ATP: R&D AS A SUBSIDY?

The importance of the international market and the presence of nationally-owned and subsidized foreign competitors are two of the most important factors distorting the marketplace in civil aviation. It is sometimes claimed that much of the money that private American companies could be expected to spend on R&D is being siphoned off instead by short-term sales battles with subsidized foreign competitors. There are several factors that make government-sponsored technology development appear to be an attractive counter to these foreign subsidies. First, R&D spending is industry-specific. It is targeted at a particular industry and does not require a broad, across-the-board policy. Second, R&D is likely to have many secondary benefits. Unlike a direct subsidy, where money is spent on one deal or item and then gone, money invested in R&D may provide paybacks in several applications far into the future. Third, R&D is a policy that can be implemented by a mission-oriented agency such as NASA, rather than the Commerce Department. This is less likely to arouse political reactions both domestically and abroad, and thus less likely to provoke a counter-response from competitors that would escalate the subsidy levels. To examine the merit of these arguments, let us consider the case of the Advanced Turboprop.

When NASA initiated the Advanced Turboprop program in 1976, they envisioned its eventual application as a twin-engined, wide-body aircraft carrying 171 passengers. As they predicted, the quest for the mid-sized airliner has been one of the focal points of the mid-1980s. All three major manufacturers of commercial aircraft are competing for this market, and each has taken a different strategy between upgrading existing equipment, designing new equipment with current technology, and aggressively developing new technology for use on all-new designs for the early 1990s. The results are instructive as to the role that R&D can play in international economic competition.

In 1984, Airbus Industries committed about $2.5 billion to develop an all-new aircraft, the A-320. Boeing and McDonnell-Douglas were selling derivatives of existing aircraft (the 737-300 and the MD-80), while developing new aircraft (the 7J7 and the MD-90 series) using the advanced turboprop (ATP) technology discussed in Chapter 5. The A-320 promised somewhat lower operating costs than the derivatives, but it was a new model and consortium-produced, both of which suggested increased development and production costs. The derivatives are far down their learning curves, and so offer lower purchase price and commonality with existing fleets but at the expense of higher operating costs. The ATP promised even higher development costs, but offered significantly lower operating costs. Each airline's choice between these aircraft would be made on the basis of purchase price, discount rate, and fuel cost, and fleet needs (age of current fleet, whether new aircraft are replacements or for growth, etc).[256]

A rough quantification of this trade-off illustrates the situation more clearly. We can estimate this by assuming that the typical 150-seat aircraft will use 1000 gallons of fuel per block-hour of operation time and that it will be operated about 2500 block-hours per year.[257] If an ATP-powered aircraft has 20 percent lower average fuel burn, it can be expected to save about 500,000 gallons of jet fuel per year. The savings will be distributed over the life of the aircraft, but it has some "net present value" at the time of purchase that depends on both price of fuel and interest rate as shown in Figure 8-1. This "equivalent initial value" (net present value at time of purchase) is the maximum increment in cost an airline would theoretically be willing to pay for an ATP-powered airliner over one powered by conventional gas turbine engines (assuming other costs, such as maintenance, are equal).

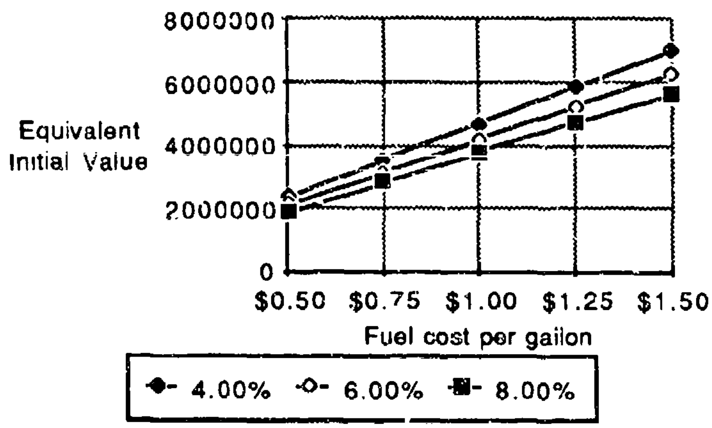

Figure 8-1. Net present value of ATP technology to an airline at the time of purchase, as a function of fuel cost and interest rate.

If aircraft were priced rationally in a free market, i.e., at a price equal to marginal cost, the manufacturer could indeed capture some of the incremental value that ATP offers its customers, i.e., charge a surcharge on ATP. The remainder of the increased value

256 At the end of 1987, World Airlines had ordered 287 A-320s, 595 MD-80s, and 759 B-737-300s, -400s, and -500s. "Airliner Census", *Flight International*, 26 December 1987.

257 These are typical utilizations for the MD-80. See *Aviation Week & Space Technology*, August 13, 1984.

would be divided between the engine companies, the airlines, and the passengers. The promise of this surcharge would encourage private companies to develop ATP independently of any U.S. government initiatives.

But this is not a free market, and aircraft are not priced rationally. Airbus products are allegedly subsidized by their governments on the order of $8 million per copy.[258] Firm documentation is generally not available, but the Indian Airways example cited in Chapter 4 suggests that American companies are cutting their prices significantly as deemed necessary to compete. In this example the airliners offered approximately equal levels of technology. Thus, money that American companies would, under free market conditions, have available to invest in ATP research may be going instead to counter the production subsidies of its foreign competitors. (There are other factors on both sides. American derivative airliners benefit from lower unit costs due to long production runs; on the other hand, development of Airbus products is also funded by the governments.)

The U.S. government has four choices. It can adopt a *laissez-faire* approach and do nothing, it can try to stop the foreign subsidies, it can counter the subsidies directly, or it can counter the subsidies indirectly.

To date the government has chosen the second option, attempting to discourage the Europeans from their practice of funding new development projects from government treasuries. Although this has met with some success in terms of eliminating the most blatant trading practices, it seems to have provoked a backlash in the case of development subsidies.[259]

If the government chose to match the subsidies the costs would be high. Assuming 60 aircraft per year for ten years at $8 million a copy implies a total cost of about $4.8 billion in constant dollars. Discounting this to the present lowers the cost to about $1.5 billion.[260] This is equivalent to having the government offer to underwrite all the development costs of the aircraft (which the Europeans also did). The SST experience

258 *The Economist*, December 13, 1986, p. 77. Over the past twelve years, Airbus has delivered 350 airliners while receiving direct government supports of over $10 billion, or a subsidy of about $28.5 million apiece. The A-320 sales to Air India (*Economist*, September 28, 1985, p. 67) suggest that in the case of the A-320 the direct subsidy is about $8M per copy.

259 See "Europeans Criticize U.S. Subsidy Charges at A-320 Rollout," (*Aviation Week & Space Technology*, February 23, 1987, p. 30), and "U.S., Europeans Clash Over Airbus Subsidies," *AW&ST*, February 9, 1987, p. 18.

260 Assuming a real interest rate of 6%.

(where the government spent $700 million) suggests that the political costs of such a large and direct subsidy would be prohibitive.

Suppose that instead of direct cash subsidies, however, the government offered an "equivalent subsidy," by developing ATP technology for the industry. For simplicity, let us take the middle value of Figure 8-1 and call the "equivalent value" of ATP $4 million per copy. If the government spends $15 million a year for 10 years (the level of the ATP program as originally proposed), and then 5 years later sales begin at the level of 60 aircraft per year and continue for ten years, the government will have provided an "equivalent subsidy" of $2.4 billion for an outlay of $150 million. When the time value of money is included this produces an internal rate of return of just over 20 percent. But we have already noted that the economic benefits of the ATP will be divided among engine companies, airframe companies, airlines, and passengers--with the exact distribution unknowable but dependent on price elasticities and the degree of competition. As a first guess let us assume the benefits are divided evenly--so the manufacturers would receive a "subsidy" of about $1 million per copy. This drops the "equivalent subsidy" proved by the government to about $600M (NPV = 75M with 6 percent discount rate), and the government's internal rate of return to about 9.5 percent. The government might be better off giving the money directly to the companies and letting them invest in CDs.

The calculations above make very favorable assumptions about the "subsidy value" of R&D (for example, there must be considerable private investment to use the new technology in an actual product). There are, of course, several other important limits to the utility of R&D as a subsidy. One of the most important is uncertainty. Even today, ten years after the start of the ATP program, it is unclear what the economic outcome of the program actually will be. Another limit is that R&D is tied to technological opportunity. R&D funding cannot be applied in arbitrary amounts the way a direct subsidy can. In the example above, ATP would offer a potential subsidy of $4 million per copy, which is only half the subsidy currently offered by European governments. No matter how much it invests in R&D, the U.S. government cannot decree that ATP technology will result in an $8 million per copy effective subsidy.[261] Research and technology development has little or no short-term impact; it is purely designed for the long run. This may be acceptable in a

261 If the U.S. chose to offer both R&D and still chose to match total subsidy payment, i.e., spent $15 million per year on R&D and then offer a $4 million per copy direct subsidy, this would reduce the NPV of the subsidy from $1.4 billion to about $850 million, a net savings of about $625 million.

situation like the present, where American companies are in dominant positions to begin with and do not require immediate relief. But in other situations immediacy may be more critical. Finally, it is difficult to prohibit foreign use of the technology once it is developed. It is the aerodynamic configuration of the A-320 (where the engines are mounted under wings) which makes it difficult for Airbus to use the ATP rather than any governmental restriction. In fact, General Electric has a French partner, SNECMA, in the development of its ATP, the Unducted Fan. This further dilutes the utility of ATP as a subsidy to American airframe companies (though not necessarily to American engine companies, such as GE).

Overall, then, the ATP example suggests that even in the most favorable circumstances imaginable, the value of technology development as a "subsidy" to American manufacturers is limited.

8.5 CONCLUSIONS

Three basic conclusions may be drawn from this brief examination. The first concerns the nature of technology development. The case studies here suggest that technology is a dynamic process rather than an object. As such, it is difficult to protect if it is to be used. Further, NASA has benefited importantly from outsiders. Overall, restrictions on NASA technology seem to be both futile and unwise.

The second observation is about technology development and international competitiveness. Two major prerequisites to a modern aircraft development program are technology and money. The two are interchangeable to some extent, but there is a very long time constant in the exchange. Technology development is crucial to long-term competitiveness, and it is clearly in the public and private interest to make sure that American companies retain technological competence. This does not mean that technology development is an effective subsidy, however, particularly in the short term when compared to other alternatives. Even with a set of favorable assumptions, government funding of ATP technology development is not effective as a subsidy.

Finally, what can be said about international cooperation in technology development? The question of whether NASA should have joint international aero programs is difficult: On the one hand, case studies show that such programs have been effective and practical. On the other, if technology is supported as an alternative to subsidies, it seems imprudent to give it away. Appropriateness of NASA international cooperation varies on situation, and why it is appropriate for NASA to support the technology at all.

When NASA is supporting technology with perceived private sector gains, it does not seem advisable to engage in joint international programs. These are likely to be areas subject to international competition, and advanced technology is one of U.S. industry's important strengths. It seems counterproductive to dilute such strength through international cooperation in technology development (though paradoxically, international cooperation in product development seems destined to continue, to insure market access and provide development funds).

When the technology is neutral, such as defense, international cooperation is more appropriate. Aeronautical R&D appears to meet the general criteria for areas where cooperation may prove valuable: the technical competence of many Western partners is high, many of the problems are shared, and in many cases the costs are large relative to overall budgets. Joint international programs can reduce the costs and distribute the risks, while at the same time building institutional support for NASA projects. Even in areas not of current priority, such as STOL, NASA should consider international partnerships as a means of keeping abreast in fields being pursued by other nations.

When the private sector incentives are negative, international cooperation seems very appropriate and perhaps highly advisable. Areas like aircraft noise reduction and control of environmental emissions are common concerns, and when the other criteria listed above are fulfilled, NASA should be encouraged to engage in international partnerships.

CHAPTER 9. OBSERVATIONS ABOUT NASA SUPPORT OF AERONAUTICAL R&D

Each of the preceding four chapters has focused on a specific circumstance that may justify government involvement in aeronautical research. The goal of this chapter is to draw together the accumulated lessons and present them as a general set of guidelines for steering future policy.

In extracting such overall conclusions, a distinction must be made about whether the goal is to provide general guidance about how the government should approach aeronautical R&D or whether it is to provide specific suggestions about the ways NASA should conduct its business. The case studies offer lessons for both. An obvious caveat should be stated that these conclusions are drawn from a very limited sample of NASA programs, and that the programs of other organizations have been studied only to the extent that they influenced or interfaced with NASA efforts. I fully expect that a broader investigation would tend to reinforce the discussion and conclusions presented here, but such a proposition can only be tested by further research.

The case studies confirm many common observations about the R&D process; for example, that the results of R&D activities are frequently different from those originally anticipated; that it is difficult if not impossible to link levels of spending on basic research with specific levels of return; and that research frequently takes years before providing economic returns. Several conclusions consistently emerge, however, that differ somewhat from conventional wisdom or common perceptions. Among these are that:

1. NASA's demonstration programs have had mixed results. *In general, the technical goals laid out for these programs have been accomplished more successfully than the policy goals. The public benefits of the successes, however, appear to far outweigh the costs of the disappointments.*

The success of NASA's research and technology development programs have sometimes led the agency to take the next step, that of applying technology to solve specific national problems. These efforts have variously been called "proof-of-concept," "demonstration," or "special" programs. Whatever they are called, NASA's full-scale demonstration efforts have almost always been technically successful, yet many have had trouble making the next transition from demonstration into operational use. The Acoustic Nacelle, Quiet Engine, and Refan programs, for example, all achieved their initial technical goals, but none of them were applied as originally envisioned. The OV-10 Rotating Cylinder Flap, Augmentor Wing, and Quiet STOL Research Aircraft (QSRA) were technically successful, but market conditions changed so that the ideas have not yet become commercially attractive.

There are, of course, exceptions in both extremes. The Advanced Turboprop, Quiet Clean General Aviation Turbine, and XV-15 Tilt Rotor are technical successes that have moved (or are moving) rapidly into operational use almost exactly as originally envisioned. The Hypersonic Research Engine, on the other hand, failed to meet almost all of its original technical goals and proved to be a conceptual dead end.

The public benefits from the programs that have been successful appear to have been very large. The JT-8D-109 REFAN engine was never adopted for the retrofit purposes for which it was originally intended, but served as a crucial element in the creation of the MD-80 family of derivative aircraft. To date some 1800 JT-8D-200 series engines have been sold. The fuel savings from these engines compared to earlier models is worth approximately \$2.7 billion.[262] Assuming that these savings are passed on to consumers largely in the form of lower ticket prices (a fair assumption in the turbulent market that has followed deregulation), this can be considered a public benefit. Further, a strong argument can be made that the MD-80 has been responsible for keeping McDonnell-Douglas in the commercial aircraft field. The \$45 million spent on REFAN must be considered an extremely good investment compared to the financial or political costs of preserving competition within the domestic aircraft industry through other means.

The Advanced Turboprop has not reached production status at this writing, but several systems are in product development and show every sign of having a significant economic impact on the next generation of short-range airliners. The potential market for

262 This assumes that the -200 series has approximately 12% better fuel economy than earlier models of the JT-8D which use about 500 gallons of fuel per block-hour of operation, that each engine is operated an average of 2500 block-hours per year for ten years, that jet fuel costs an average of \$1/gallon, and that operations and maintenance costs for the -200 series are not appreciably different than earlier models. 1800 engines would consume about \$22.5 billion worth of fuel, or an expected savings of about \$2.7 billion.

such engines is huge,[263] but it is probably unfair to credit the entire market for ATP to NASA since the ATP would probably have been developed eventually. Even if the NASA program is credited only with accelerating the introduction of ATP by ten years, it can still be expected to produce a savings (in current prices) of about $2.4 billion.[264]

The XV-15 Tilt Rotor, which cost NASA around $25 million, has led directly to the V-22 Osprey, currently under development for all four military services (and with commercial derivatives sure to follow). Over 900 V-22s are currently planned for procurement, with an estimated procurement cost of about $18 billion and a life-cycle cost of about $31 billion. The JVX source selection document estimated that the nearest competitor to the tilt-rotor concept would have cost over $2 billion more.[265] This amount is, in effect, a direct public benefit from the XV-15 investment.

These three examples alone (REFAN, ATP, and XV-15) provide gross public benefits of over $7 billion at a NASA cost of perhaps $250 million. Since the total NASA investment in all of aeronautics during the past 25 years has been only about $8.3 billion, it seems clear that the benefits from only a few major successes (and there have surely been many others) outweigh the costs of those concepts that have not met their original expectations.

2. *Demonstration programs in aeronautics should continue.*

That previous programs have proved economically justifiable investments in the public interest is not an argument for specific future programs. It is an argument, however, for the admissibility of demonstration programs as a class. Demonstration programs serve three important functions. First, they provide an interdisciplinary focus for the research. Aeronautical vehicles are complex systems, and while great progress can be made in individual elements (for example, algorithms for computational fluid dynamics) it is only in the context of a system that the value and direction of these elements can be fully realized. Second, demonstration vehicles provide unique sources of data. Complex vehicles such as the tilt-rotor may be analyzed exhaustively in the wind tunnel or the computer, but only through attempts to demonstrate them in the real world do such factors as reliability become

263 Estimates for the number of short range transports in the 150-seat category needed during the 1990s range from about 2500 to about 4000 units. See *Flight International*, "The Independent View," 15 March 1986, p. 9.

264 See Section 8.4 for this calculation.

265 See Center for Naval Analyses, *Cost and Operational Effectiveness of the JVX for the Marine Corps Assault Mission*, CNR 104, August 1985.

fully evident. Finally, such programs are an important method of building confidence among potential users. Since, as is widely noted, such demonstration programs tend to be large and expensive compared to more fundamental research, they should be evaluated carefully.

An important part of the evaluation process is more clarity between "prototypes" and "demonstrators." Prototype aircraft are designed and tested in accordance with a specification prepared to procure an airplane that will meet an operational requirement, and thus are intended to precede serial production.[266] Experimental, demonstration, proof-of-concept, technology validation aircraft are not. Rather, they are developed (either by a completely new design or by modification to existing aircraft) to obtain knowledge without intent to place the technology into production or operational use. A third class of "research" aircraft should be distinguished, which serve as flying laboratories for other scientific research, such as the ER-2, zero-gravity KC-135, or infrared-telescope-carrying C-141.

3. The government can and should include commercial considerations when selecting demonstration programs.

It is widely suggested that government support of R&D is most justifiable at the level of basic research and that the government should strictly avoid making market-oriented decisions or trying to pick commercial "winners" (the FAA's SST program is the most frequently-cited example).[267] Yet many of the NASA programs that have had the strongest and most direct impact are those that went the farthest towards commercial development. The JT-8D-109 REFAN engine, developed in 1973-75 as a possible retrofit option for existing aircraft, formed the basis of the engine that today powers a very successful derivative aircraft, the McDonnell-Douglas MD-80. Another NASA program, the Quiet Clean General Aviation Turbine (QCGAT) contributed to the development of the best-selling turbofan engine currently available for business aircraft. The government did not attempt to determine which systems should actually be placed into production, but they did fund technology readiness to support that decision. The key is to recognize that there is a distinction between technology development and product development, but that this line becomes very vague as the decision to initiate product development approaches. The

266 Appendix F, "The Research Aircraft Program," in *Aeronautical Research and Technology Policy*, Office of Science and Technology Policy, Volume II, November 1982.

267 See, for example, Richard R. Nelson, *Government and Technical Progress, A Cross-Industry Analysis*, pp. 469-470.

government cannot avoid making market-oriented decisions and it should concentrate on making them wisely rather than on attempting to avoid them.

4. Government R&D programs generally stimulate, rather than discourage, private investment.

Another commonly-suggested guideline is that the government should avoid any area with prospective commercial benefits for the private sector on the grounds that such involvement at best constitutes a subsidy to the private sector and at worst drives out private investment.[268] No evidence of the latter effect can be seen in the case studies; indeed, there is evidence that when private companies perceive a commercial advantage in a NASA program, their willingness to invest has not been constrained by previous government decisions. The General Electric Company's "Unducted Fan" (UDF) grew out of the NASA Advanced Turboprop Program, but it represents a distinctly different technical approach than NASA envisioned originally. When NASA originated the ATP program in 1976, GE opposed it in favor of near-term work on existing engines. By 1981, however, the results of ATP looked sufficiently promising for GE to launch its UDF program, which soon outpaced the NASA program that had spawned it. The NASA program was subsequently realigned in support of the private effort.

5. By coupling public R&D with private product development in areas with potential public returns, the government can achieve highly leveraged returns.

As to the question of whether R&D constitutes an unwarranted subsidy, the case studies show clearly that public benefits, even where they are small in comparison to potential private benefits, sometimes do justify government investment in R&D. Both STOL and ATP were examples of situations where both public and private benefits were expected to accrue from the development of new technology. In each case, private incentives were arguably positive for developing and marketing an actual product but were greatly reduced by the additional cost, time, and uncertainty of the needed research and technology development program. By funding this R&D program, the government was rationally able to seek public returns by stimulating the private sector. By thus coupling the programs, the government expected to obtain highly leveraged benefits from its R&D investment. As is typical in highly speculative investments, some areas (such as STOL)

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268 See, for example, the Office of Management and Budget, *Special Analysis K, Fiscal Year 1983 Budget*.

have so far failed to pay off. The cases that do pay off, such as the ATP, REFAN, or the XV-15 Tilt-Rotor, appear to have such high leverage that they may cover the costs of many unsuccessful programs.

6. Cost-benefit analysis has an important role to play in planning demonstration programs.

One of the most important questions surrounding the use of investment tools such as cost-benefit analysis is whether it is really reasonable to analyze proposed R&D programs on the basis of expected applications, when studies (including this one) consistently show that the most important benefits of R&D are often unknown when the research is initiated. Many in NASA have come to argue that, in effect, prospective justification of R&D is impossible.[269]

Such an attitude is both dangerous and incorrect. Without some estimate of potential benefits, there is no rational way to make the difficult resource allocation questions that must be made in the real world. In the absence of a rational method, irrationality will prevail. By failing to make ordered choices on an understandable basis, NASA merely defers the choices to outsiders (OMB, Congress, the GAO) who, in general, lack either a detailed understanding of the issues or any sense of continuity and perspective.

Estimating potential benefits is not like making technical calculations of, say, aircraft performance, where increased sophistication is correlated with increased accuracy. The *actual* applications are impossible to gauge; what counts is that potential applications be gauged and evaluated. This uncertainty means that the analysis must be structured broadly. Further, it must be updated periodically as new information becomes available. By making explicit the external considerations behind a decision to conduct R&D, cost-benefit analysis keeps decisionmakers aware of changes in the overall environment. Such analysis makes clear, for example, the importance of traffic growth rate for STOL or the price of fuel as a driver of ATP. No analysis can predict the future (the traffic level did not increase as projected in STOL, but fuel costs increased faster in the ATP) but simple quantitative techniques can assist in monitoring and assessing the progress and importance of continued R&T. This is particularly important as technology comes closer to actual applications, and is essential before embarking on demonstration programs.

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269 See Hans Mark and Arnold Levine, *The Management of Research Institutions: A Look at Government Laboratories* (NASA SP-481, 1984), p. 90.

7. NASA's lack of operational responsibilities is an important key to its effectiveness in conducting R&D in aeronautics.

It is commonly assumed that only an operational agency can truly understand the problems it faces and thus that agencies like the DoD or FAA should have primary responsibility for R&D in their areas, with NASA playing a supporting (if any) role.[270] The Air Force's treatment of STOL or scramjets, the FAA's involvement with supersonic transports or quiet engines, and even NASA's involvement with the Shuttle, suggest that operational agencies alternate between seeing no application for a given technology--and thus no justification for supporting R&D--and pressing for an immediate application, with a prototype of an operational system needed as rapidly as possible. Further, there is a tendency for research programs to be perceived as competition to development of current-generation systems. This is precisely the wrong environment for the type of focused, long-term research that has led to truly radical advances.

All of the case studies suggest that NASA's lack of operational responsibilities in aeronautics is beneficial to its role as a research agency. On the other hand, its lack of operational responsibilities means that NASA needs to maintain close contacts with potential users in order to ensure that the technology that is developed is well matched to actual needs. In general, cooperative programs seem to have fared well. The XV-15 and ATP have met with acceptance; both involved cost sharing with potential users in the later, more expensive phases of the demonstration. The QSRA did not; in fact, its predecessor, the QUESTOL, had been cancelled precisely because anticipated industry co-sponsorship failed to materialize.

Interagency coordination seems to have been most successful either when the interagency effort was being steered from above (as when the Office of Science and Technology led the governmental noise reduction effort) or when NASA's partner agency did not have a primary mission in aviation research per se, but rather saw it as a means to an end. The joint rotorcraft program conducted with the Army or the propeller noise reduction work with the EPA are examples of this success.

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270 Robert McNamara, when he was Secretary of Defense, went so far as to propose that any militarily-related aeronautical R&D conducted by NASA be done under a cost-reimbursable contract. See Arnold S. Levine, *Managing NASA in the Apollo Era*, Chapter 8.

8. Many aeronautical R&D programs have potential benefits in several areas, requiring an agency with a broad charter to evaluate them properly.

The analyses in Chapters 4-8 showed that in each of the various circumstances where government involvement in aeronautical R&D is justified, R&D is frequently better conducted by a dedicated R&D agency such as NASA than by a government agency with operational responsibilities in that field. This conclusion is even more strongly reinforced by the fact that many technologies offer potential applications in several fields, and thus span several of the circumstances heretofore treated as unique. STOL aircraft could be used to deliver passengers to small airports close to urban areas, or to deliver troops to unprepared airports near the front lines. The Tilt-Rotor could be used to commute between city centers or between aircraft carriers. Quiet engines could be used to reduce annoyance of residents near civil airports or to provide stealth qualities for military aircraft. The advanced turboprop would be valuable even without the consideration of foreign competition, but offers a particular opportunity as a response to foreign subsidies.

The argument was made in Chapter 5 that the government should be particularly alert for situations where there are multiple beneficiaries but no simple way of sharing costs, for these programs typically fare poorly in cost-benefit analysis because partial benefits are compared with essentially full costs. The same argument applies to aeronautical R&D programs which may have potential benefits in several circumstances. If the total development costs are compared to the benefits derived by any one sector, the investment may appear to be unattractive, especially when weighted for uncertainty. If the total benefits are considered together, however, the program appears quite attractive compared to the costs. Few operational agencies have much incentive to consider factors outside their particular mission. Further, some operational agencies are legally prohibited from considering factors outside their charter. The Department of Defense, for example, is restricted by the Mansfield Amendment[271] to R&D with "foreseeable military applications." The role of a dedicated R&D agency is precisely to span the categories and evaluate the total costs and benefits of a program. In aeronautics, NASA is uniquely suited to this role.

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271 P.L. 91-121, Section 203, which states: "None of the funds authorized or appropriated by this act may be used to carry out any research project or study unless such project or study has a direct and apparent relationship to a specific military function or operation."

9. A strong and consistent technology base is vital for the future.

Many of the ideas that grew to be large NASA programs originated outside of NASA. In the noise example, for instance, much of the original work on understanding and reducing jet noise was done in England. In STOL, the British were responsible for the original work on the jet flap, the Canadians for its initial development into the Augmentor Wing, and the French for the blown-flap propeller. In hypersonics, many of the original proposals came out of small American companies. Where NASA has proved particularly adept is taking these unexplored concepts and developing them to the point that they can be applied in practical systems.[272]

This process is most appropriately described as *focused research.* Examples can be drawn from every case study--for example, sound-absorbing material (SAM) for aircraft noise reduction. The concept of SAM did not originate in NASA, and had in fact been used before NASA ever entered the field. But its potential utility was estimated to be very low and it was not being actively pursued. NASA stepped in and was able to combine theoretical analysis with a unique flow-testing facility to produce a rapid increase in SAM effectiveness. This was then tested in actual engine designs under NASA auspices. SAM alone allowed some existing aircraft to meet Federal noise regulations, and the materials have since been used in the nacelles of essentially every modern commercial jet engine.

The key ingredients in focused research seem to include: (1) the availability of experienced people from many disciplines, (2) dedicated research facilities (i.e., not also in use for production development), and (3) a research-oriented environment (a key internal measure of effectiveness at NASA, for example, is the number of papers a researcher publishes. This is similar to a university, and a stark contrast to most private companies).

Most of this work is what the NSF would describe as applied, rather than basic, research. NASA considers it part of its "Research and Technology Base." A key feature of focused research is that it is aimed at the development of a specific technology with a general application in mind. For example, although NASA did not know that SAM would be used in the Boeing 757, USB in the YC-14, or scramjets in the X-30, they did have goals of developing noise reduction technology for subsonic commercial transports,

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272 This conclusion is reinforced by other examples not detailed here, among them the development of turbojet engines or supercritical airfoils. In each case the original work was done elsewhere, but NASA stepped in late with a focused program that eventually became extremely important to the development of the field.

powered-lift for subsonic transport, or hypersonic propulsion for space-launch or hypersonic cruise.

The value of these programs is widely recognized. The issues are how much to spend on focused research and what the relationship should be between these programs and technology demonstrations. In recent years demonstration programs have sometimes been portrayed as competitors to more fundamental research, and in some instances this has no doubt been true.[273] But as a general conclusion this seems unjustified. The case studies suggest that a logical way to view demonstration programs is as a complement to focused research. Demonstration programs provide identifiable, quantifiable benefits. Since they draw upon the technology base, one way to justify that base is to couple it explicitly to demonstration programs. This linkage is necessarily indirect, since focused technology programs must be initiated years before the need for a near-term demonstration program can be identified.

10. *Clearer assessments of public benefits are needed.*

NASA needs to develop a clearer assessment of public-sector costs and benefits, and the circumstances that justify government involvement. Many of the NASA programs appear to have been driven largely by technological opportunity; when the agency has examined the economics of new technology, it has usually stopped short of asking why government involvement is required specifically or how responsibility should be divided between public and private sectors. The study suggests that there are specific strategies that NASA should pursue, depending on the circumstance that justifies government involvement. The study suggests that there are three basic strategies that NASA should pursue, depending on whether private sector incentives are positive, negative, or neutral:

Private sector incentives perceived positive. In general, the government should stay out of areas where the private sector has positive economic incentives. The study notes the severe distortions to a free market that exist in aeronautics, and concludes that even when positive, appropriable economic benefits may appear to exist for the private sector, various factors may lead the private sector to undervalue the research. The most common case is where the benefits are not fully appropriable (i.e., a development offers both public and private benefits) but the costs are not readily allocable. The government's

[273] As demonstration programs have been eliminated, the specificity of the NASA aeronautics budget has been reduced. This appears to have been coupled: as the programs with the most specific goals have been reduced, the goals of the remaining research have been made more ambiguous.

goal should be to secure public benefits at minimum cost by using government R&D to stimulate the private sector. Since public and private benefits are thus linked, the government should continue its R&D either until the net present value seen by the private sector becomes positive, or until the net present value seen by the public sector becomes negative. In such cases the government's marginal return on investment can be expected to exhibit a discrete step function: below a certain investment threshold, there are no public returns because the private sector's confidence has not been established sufficiently to launch its own commercial program. Beyond a certain point, however, private investment begins and public returns then rise to very large levels. Above this point, the public's marginal returns decrease since the public benefits are generated by the private program, and further public spending merely dilutes its returns.

Private sector incentives are perceived negative. Just as market economics sometimes understate net public benefits of an activity in private-sector calculations, so they sometimes understate public disbenefits (airlines, for example, see no net cost in the production of noise, while people living under a flight path obviously do). In such cases government regulation is frequently a response. Such regulatory intervention has occurred extensively in aeronautics, and it inevitably shifts incentives for R&D. In such situations, NASA should have two goals. The first is to provide options and data to support the rational and effective promulgation of rules, acting as the interface between a reluctant industry and an administrative (i.e., essentially non-technical) regulatory agency. The second goal is to provide a "technology push" to complement the "market pull" of regulation, with the technology available in advance of (or at least parallel with) the regulation. Such parallelism allows a much more realistic assessment of the true regulatory impact. The noise case study strongly suggests that Federal regulatory agencies act, in practice, as adjudicatory bodies, choosing between a selection of currently available options. Industry inevitably promotes the option imposing minimum impact on their operations. Thus, NASA filled a unique role by developing and by demonstrating new options. Although many in NASA viewed their noise reduction demonstration programs as going far beyond the agency's proper role, in retrospect some of these programs do not appear to have gone quite far enough. Had NASA chosen to build its Quiet Engine around a properly-sized core, rather than around a significantly de-rated core of the much larger CF-6, it is quite possible that a quiet engine suitable for retrofit of the JT-3D would have been available at least five years sooner than actually occurred. Likewise, if the JT-8D-109 REFAN had been scaled more appropriately for its retrofit targets it might have been adopted; the subsequent increase in fuel prices would have meant that the airlines who invested in refan technology (which offered lower fuel consumption in addition to reduced noise) would have actually had a higher rate of return than those that did not.

All the goods are public, so that private sector incentives are essentially neutral. The issue here is not so much whether the government should be involved in R&D, but whether the responsibility for R&D should be delegated to a dedicated R&D agency like NASA or reside in the cognizant "operational" agency such as DoD or the FAA. The analysis presented here shows that the long-term, focused research necessary to produce dramatic advances is better suited to a dedicated R&D agency where it is not forced to compete with existing systems.

11. Support of R&D is unlikely to be an effective subsidy for promoting near-term international competitiveness.

R&D is frequently discussed as a strategy for ensuring the competitiveness of American companies in the face of nationally-supported foreign competition. This study suggests that while government-supported R&D is vital for the long-term international competitiveness of the U.S. industry, it is not an effective replacement for or counter to direct production subsidies. R&D is long-term, and thus neither very specific nor timely. If near-term relief is truly appropriate, other techniques must be used to provide it.

12. International cooperative R&D programs deserve greater attention.

The question of whether NASA should have joint international aero programs is difficult. On the one hand, case studies show that such programs have been effective and practical. On the other, if technology is supported as an alternative to subsidies, it seems imprudent to give it away. Appropriateness of NASA international cooperation varies on situation, and why it is appropriate for NASA to support the technology at all.

When NASA is supporting technology with perceived private sector gains, it does not seem advisable to engage in joint international programs. These are likely to be areas subject to international competition, and advanced technology is one of U.S. industry's important strengths. It seems counterproductive to dilute such strength through international cooperation in technology development (though paradoxically, international cooperation in product development seems destined to continue, to ensure market access and provide development funds).

When the technology is neutral, such as defense, international cooperation is more appropriate. Aeronautical R&D appears to meet the general criteria for areas where cooperation may prove valuable: the technical competence of many Western partners is high, many of the problems are shared, and in many cases the costs are large relative to overall budgets. Joint international programs can reduce the costs and distribute the risks, while at the same time building institutional support for NASA projects. Even in areas not of current priority, such as STOL, NASA should consider international partnerships as a means of keeping abreast in fields being pursued by other nations.

When the private sector incentives are negative, international cooperation seems very appropriate and perhaps highly advisable. Areas like aircraft noise reduction and control of environmental emissions are common concerns, and when the other criteria listed above are fulfilled, NASA should be encouraged to engage in international partnerships.

13. More retrospective studies are needed.

Every major NASA aeronautical program should conclude with some retrospective review that compares its original goals, both technical and policy-oriented, with its results. There need be no requirement for consensus; multiple views and interpretations are desirable. Similarly, there is no requirement for immediacy; the true impact of a research program may not be known for many years. What is needed is some means of ensuring that retrospective reviews do not become retroactive justifications or apologia. This means that the participation of first-hand participants needs to be balanced by outside views, perhaps provided by the NASA History Office, the research staff of the National Air and Space Museum, or the National Research Council.

14. Aeronautics may be limited as a model for other areas of government involvement.

In many ways, government support of aeronautical research has been a highly productive national investment. As such, important questions arise about how applicable this experience may be to other areas of government involvement in technology. Although no comprehensive examination of this issue was undertaken in this study, a quick look suggests that there are important limits. First are some unique features of the marketplace. As we have seen in Chapter 4, the government totally dominates the aeronautics marketplace: 50 percent of aeronautical products are purchased directly by the U.S. government and roughly 90 percent are purchased directly or indirectly by governments. R&D constitutes an extremely large fraction of sales. Although technology is still advancing rapidly compared with many other areas of transportation, the industry is relatively mature, with high barriers to entry and exit, especially in production. Further, aeronautical vehicles tend to have high unit costs. They are in a region where the utility of prototypes is marginal: in systems with much lower costs--automobiles, for example--it is quite feasible to build a prototype; but for large vehicles such as aircraft carriers, no one builds a prototype.

In aeronautical R&D, there can be no question that a benefit stream exists and can be quantified; the problem is one of distributing the costs. Defense expenditures are generally funded through general taxes. R&D directed towards civil applications could more appropriately be charged to users of the civil air transportation network, but in the absence of modifications to the Airport Trust Fund or other sources, general taxes are an acceptable stand-in.

This situation is a contrast to many other areas of "science policy" such as basic science, space science, or even manned space flight. These produce no tangible short-term benefits and have no quantifiable benefit stream, therefore, cost-benefit analysis is not an appropriate tool. It is not feasible to identify specific beneficiaries and thus to consider a direct tax.

15. Aeronautical R&D is a national investment, and should be evaluated as such.

The overall conclusion from the case studies examined here is that, despite the long payback period and uncertain returns, aeronautical R&D is inherently practical. Every day the nation's commercial and military well-being is shaped by aeronautical vehicles, which are directly and continuously influenced by aeronautical research and development. In this sense the field is fundamentally different from others such as high-energy physics or space science. The logic and arguments used to plan and defend the NASA aeronautics program should be grounded in an explainable and constantly updated evaluation of the potential national worth of the program and its elements.

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